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Trends in climate parameters affecting winegrape ripening in northeastern Slovenia

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ABSTRACT: This study examined the structure and trends in climate parameters that were important for grapevine growing between 1950 and 2009 in the wine-growing region of Styria in NE Slovenia. The study also included the dynamics of grape ripening and the timing of harvest for 4 varieties grown in the region between 1980 and 2009. Temperature and precipitation characteristics from 3 stations (Celje, Jeruzalem, and Maribor) in the region were organized into annual and growing-season periods and were used to assess the effects on the different varieties and on wine quality. Based on the data associated with the content of soluble solids, total acidity, and the recommended date of harvest for a particular year, trends towards earlier maturity of 12–25 d were observed. In general, temperature changes were more significant after 1980 than between 1950 and 1979. The mean annual and seasonal temperatures (1980–2009) increased significantly, by 0.4 to 0.6°C per decade. The average growing-season warming rates were driven particularly by changes in maximum temperatures, with significant increases in the number of days with $T_{max} >$ 30°C. Growing-season warming has also resulted in changes in heat accumulation indices, with significant increases since 1980. Changes in temperature parameters show strong correlations with harvest dates and fruit composition. Trends toward higher sugar levels and lower total acidity are a consequence of higher temperatures during the ripening of the berries. Grapes now ripen at temperatures that are approximately 1.2–1.8°C higher than 30 yr ago. For varieties that ripen early, the temperatures are predicted to become too hot to produce high-quality wines.

KEY WORDS: Climate change · Temperature · Vine varieties · Grape maturity · Slovenia

1. INTRODUCTION

Warming in western and northern Europe is projected to increase between 2.5 and 4.5°C by the end of the 21st century, and most climate models predict an increase in precipitation rates during winter (Schultz & Lebon 2005). In the last 20 yr, warming trends have been noted in all periods of the year (Branković et al. 2010). In the Northern Hemisphere warming will be stronger in the cooler half of the year. Milder winters and warmer summers are expected, and extremely high temperatures will occur more often, whereas the risk of low temperatures is expected to be lower (Kohler 2009). Many researchers have examined the impact of climate change on the viability of agricultural production, examining changes in winter hardening potential, frost occurrence, growing-season length and heat, and drought stress during the growing season (Carter et al. 1991, Menzel & Fabian 1999, Jones & Davis 2000, Moonen et al. 2002, Lobell et al. 2006, Santos et al. 2007). Benefits arising from climate change are an increase in net agricultural income; however, in the long run, if temperature and precipitation changes become more severe than those simulated for 2011–2040, income losses cannot be ruled out (Lippert et. al 2009).

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The effect of climate change on agriculture will ultimately depend on the timing of plant physiological requirements and the spatial variations, seasonality, and magnitude of the warming. This is evident in viticulture, since the quality of wine results from experience and is concentrated in geographically distinct regions with many characteristic weather and climate factors (Laget et al. 2008, Kast & Rupp 2009). Spatial modeling research has indicated the potential expansion of viticultural regions, with parts of southern Europe becoming too hot to produce high-quality wines and northern regions becoming suited once again — as during the medieval period, from the 9th to the 13th centuries AD (Kenny & Harrison 1992, Laget et al. 2008, Flexas et al. 2010). Most of the world's highest quality wine producing regions have experienced growing-season warming trends over the last 50 yr. The greatest effects were in the cool climate regions. Growing-season length and temperature are critical factors in maximizing a given style of wine and its quality (Jones et al. 2005). In Australia, the effect of warming was negative if no adaptive measures are implemented, and the reduction of winegrape quality varied regionally (Webb et al. 2008). In northeastern Spain production was reduced in the warmest years (Ramos et al. 2008). Warmer conditions influence yield potential and fruit composition at harvest and lead to a shorter growing season, but an increase in yield variability (Bindi et al. 1996, Nemani et al. 2001, Webb et al. 2007, 2012, Kast & Rupp 2009, Keller 2010). In many cases, variability between years is too great to be overcome by modifying management practices (Clingeleffer 2010).

In some regions, projections show that increases in precipitation may, in turn, affect soil evolution by increasing the amount of water flowing through the soil (Montagne & Cornu 2010). Thus, climate change would significantly affect soil evolution, by inducing a loss of the finest particles of organic matter. The tendency towards increasingly extreme weather phenomena (more intense precipitation) can be seen as a result of climate change, which can increase soil erosion, particularly in vineyards on steep slopes (Vršič et al. 2011, Vršič 2012). Due to the milder winters, there will be greater pest and disease pressure (Schultz 2000, Tate 2001). Hot summers result in earlier grape ripening, and in some wine-growing regions diseases such as botrytis are more likely to appear (Petgen 2007, Prior 2007). The increase in ultraviolet-B (UV-B) radiation on the soil surface due to the decreased ozone layer can cause changes in the physiology of the vine and have a direct effect on grape composition. The aromatic profiles may change, and the aroma of white wine varieties in particular may be less marked (Schultz 2000).

The minimal thermal demand for grapevine growth is expressed as a value of the heat summation index (growing degree-days [GDD] from April to October in the Northern Hemisphere, with a base temperature of 10°C). Becker (1985) specified the minimum GDD as 1000 (°D units); however, subsequent research has found the minimum to be 850 (Kenny & Shao 1992, Jones et al. 2010). In the last decade, the vine development phases, such as budburst, bloom, and harvest have, on average, taken place earlier than in the 1980s (Duchêne & Schneider 2005, Duchêne et al. 2010, Jorquera-Fontena & Orrego-Verdugo 2010, Webb et al. 2011, Vršić & Vodovnik-Plevnik 2012).

Slovenia is a viticultural world in miniature (Mediterranean, Continental and Pannonian climates), including all of the world's important winegrape varieties for the production of quality wine. The aim of this research is to examine the changes in temperature and precipitation and their effect on the ripening and composition of various grapevine varieties. This is the first study of the impact of climate change on winegrape quality in Slovenia aimed at establishing the response of the particular varieties to increasing temperatures. This paper presents the results for 4 important varieties grown in the Slovenian Styria, the most extensive wine-growing region in the country, which has intermediate climate conditions.

2. DATA AND METHODS

2.1. Study area

This study was carried out using the longest available data series from 3 meteorological stations: Maribor (46° 32′ N, 15° 49′ E), Jeruzalem (46° 48′ N, 16° 19′ E), and Celje (46° 15′ N, 15° 15′ E) in the Styrian wine-growing region in NE Slovenia (Fig. 1). This region is located between the Sava and Mura Rivers. The area is geologically part of the former Pannonian Sea basin, composed of folded and poorly interlocking Neogene marine sediments, and with a transitional Pannonian continental climate. The continental climate features grow stronger with increasing distance from the Alps. The vineyards (8600 ha) are predominantly planted with white varieties, on steep slopes with inclinations of 30–50 % and at elevations of 250 to 350 m. Daily precipitation rates and temperature (mean, maximum, and minimum) recorded

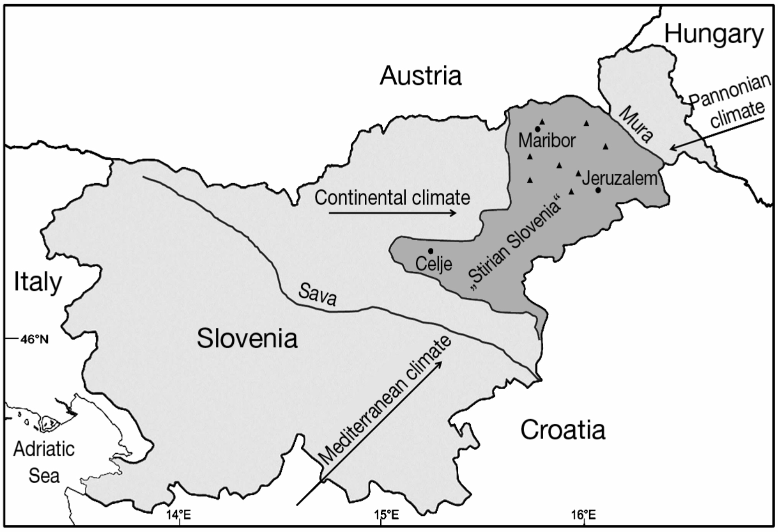

Fig. 1. Meteorological stations in the Slovenian Styrian wine-growing region (Maribor, Jeruzalem, Celje) and 8 permanent locations in sub-regions for weekly monitoring of grapevine ripening (black triangles). Gray shading shows the other areas of Slovenia

in Maribor (1950–2009; elevation 278 m), Jeruzalem (1956–2009; 345 m), and Celje (1952–2009, 244 m) were used in the analysis. The data were obtained from the archives of the Slovenian Environmental Agency (SEA).

2.2. Climate parameters and grapevine growing

An analysis of the observed climate for the periods 1961–1990 (representing the 20th century), 1950–1979, and 1980–2009 was performed. Daily data from each station were organized into annual and growing-season periods, and used to derive bioclimatic indices (Table 1). For the growing season (April–October), the precipitation and temperature (average, minimum, and maximum) from each station were summarized, since the growing-season averages usually correlate significantly with wine production and quality. The length of the frost-free period (spring–autumn) was assessed by examining the number of days with temperatures >0°C. To assess the indications of heat stress, the number of days with temperatures >30°C was determined. This temperature causes premature grape ripening (a shorter growing season), lower total acidity, and aromatic compounds (Vršič & Vodovnik-Plevnik 2012).

To obtain more information about the wine region and to determine general guidelines for the potential quality and style of wine, GDDs (Winkler et al. 1974) and the Huglin Index (HI) (Huglin 1978) were calculated. For the Northern Hemisphere, the HI (Huglin 1978) is calculated using the following formula:

$$\mathrm{HI} = \sum_{01.04}^{30.09} d \cdot \max\left[\frac{(T-10)+(T_x-10)}{2}, 0\right]$$

where T is the mean air temperature (°C), T_x is the maximum air temperature (°C), and d is the length-of-day coefficient, ranging from 1.02 to 1.06 between 40 and 50° latitude. This index enables viticultural regions to be classified in terms of the sum of temperatures required for vine development and grape ripening.

GDDs were calculated for the April–October period by summing the daily average temperatures above a base value of 10°C, where values below 10°C are set to zero:

$$\mathrm{GDD} = \sum_{01.04}^{30.10} \max[(T-10), 0]$$

The variables were assessed by descriptive statistics and trend analysis. Since some of the parameters examined in the study were not normally distributed, a nonparametric Mann-Kendall trend test (MK-test) with a 5% significance level was applied to all series (Hirsch et al. 1991), and the associated slope estimate developed by Sen (1968) was computed. In addition, all time series were tested for autocorrelation using *t*-statistics for the first-order-autocorrelation coefficient, and in some series statistically significant ($p \leq 0.1$)

Table 1. Bioclimatic parameters analyzed in this study

Variable	Description
T_{avg}	Average annual temperature, °C
T_{max}	Average annual maximum temperature, °C
T_{min}	Average annual minimum temperature, °C
GST_{avg}	Average growing season temperature (April–October), °C
GST_{max}	Average growing season maximum temperature (April–October), °C
GST_{min}	Average growing season minimum temperature (April–October), °C
P	Total annual precipitation, mm
GSP	Total growing season precipitation (April–October), mm
HI	Huglin Index, °D units
GDD	Growing degree days (April to October), °D units
NDT_{max30}	Number of days with maximum temperature >30°C
NDGS	Number of days between last and first frost (frost-free period)

autocorrelation was detected. The MK-test (Kendall 1975) is, like other distribution-free or parametric tests, very sensitive to autocorrelation. In light of this, the pre-whitening proposed by Yue et al. (2002) was used to incorporate the effect of autocorrelation. The method of pre-whitening is comprised of 4 steps. (1) Sen's estimate of the slope is computed. (2) The trend (if determined to be significant in the first step) is removed from the series. (3) The first-order autocorrelation is computed and removed from the series if it is determined to be significant. (4) The trend removed in the second step is again added to the series. The differences in climate parameters between the stations were tested with the paired-samples *t*-test.

2.3. Grapevine ripening and wine quality

Data from the weekly monitoring of grape ripening in the period from 1980 to 2009 for early, medium to late, and late-ripening vine varieties were collected and statistically analyzed. Only in this wine region are the ripening data for 15 varieties available for such a long period. The data were collected from 8 permanent locations in sub-regions of Slovenian Styria (Fig. 1) and recorded by the Agriculture and Forestry Institute in Maribor. This article presents the results for 4 varieties: Müller Thurgau (early ripening), Pinot Gris (medium to late), and Muscat Blanc and Welschriesling (late). Welschriesling, or Italian Riesling, is the most prevalent variety grown in the region.

For each variety, 200 berries were randomly sampled at each location starting in 1980. Monitoring of grape ripening began in early to mid-August, depending on how early the grapes showed signs of ripening. The harvest date was set in accordance with the Wine Act of Slovenia at the point when the total soluble solids reached approximately 76°Oe (i.e. 76° on the Oechsle scale, a hydrometer scale that measures grape must density) (18°Brix; the limit for quality wine) and 84°Oe (20°Brix; the limit for wine of superior quality). In the case of poor vintages, the harvest date was set according to the sugar content for quality wine or, in the case of very poor vintages, according to the state of health of the grapes (vintages at the beginning of the 1980s). We focus on the relationship between the bioclimatic and ripening parameters at the recommended harvest dates. Based on the data of soluble solids and total acidity in grape juice, and the recommended harvest date, a trend towards an earlier grape ripening.

To estimate quality, vintage ratings were used in this analysis. Since 1970 (after the wine law was enacted) vintage ratings have been conducted prior to the sale of wines, and the ratings represent the official average estimate of the quality of all wines. The wines are subjected to sensory evaluation by at least 5 professional oenologists from the Agricultural and Forestry Institute Maribor. For the rating of wines, the common 100-point scale is used: ≤59 very bad, 60–69 satisfactory, 70–79 average to good, 80–89 good to very good, and 90–100 excellent.

3. RESULTS AND DISCUSSION

3.1. Climate structure and trends

The general climate for Slovenian Styria is temperate continental, characterized by considerable seasonal temperature variability, cold winters, and moderately hot summers, with an annual average temperature of about 10°C (1950–2009). The long-term average rainfall in the growing season is between 648 mm in Jeruzalem and 785 mm in Celje (Table 2), and the precipitation is more or less equally distributed over the year. For winegrape maturity potential, the region is considered intermediate, based on the average growing-season temperature (GST_{avg}) (Jones 2006), with 15.4°C in the period 1950–2009. In the period before the 1980s and in the reference period 1961–1990, GST_{avg} was below or close to 15°C. During the period 1980–2009, GST_{avg} was close to 16°C (Table 2).

For the reference period (1961–1990) and the period 1950–1979, only minor changes in bioclimatic parameters were observed (Table 2). From this, we can conclude that the greatest rate of warming began after the 1990s, and this has led to large changes in bioclimatic parameters from 1980 to 2009. Similar results were found by Jones et. al (2005), i.e. that the GST_{avg} in almost all wine regions increased dramatically after the 1990s.

Changes between 1980 and 2009 generally appear to be the most dramatic. Significant trends towards growing-season warming have been observed in GST_{avg} at all 3 stations. Warming was due to changes in both the GST_{min} and GST_{max}, but the changes in GST_{max} were greater. GST_{avg} trends ranged from 0.4°C decade^{-1} in Jeruzalem to 0.6°C decade^{-1} in Maribor (Table 2). The growing-season maximum temperature extremes (NDT_{max30}; see Table 2) significantly increased at all locations, with the average

Table 2. Descriptive and Mann-Kendall test statistics after pre-whitening for bioclimatic parameters (see Table 1 for abbreviations) for 4 periods for the 3 meteorological stations Celje (1952–2009), Jeruzalem (1956–2009) and Maribor (1950–2009). *b*: Sen's estimate of slope; tau: Mann-Kendall correlation coefficients; p: significance of Mann-Kendall test, where in cases of significant first-order autocorrelation method of pre-whitening is performed ($p \leq 0.05$); **bold**: significant

	1952–1979					1980–2009					1952–2009					1961–1990				
	Mean	SD	b	tau	p	Mean	SD	b	tau	p	Mean	SD	b	tau	p	Mean	SD	b	tau	p
Celje																				
T_{avg}	9.06	0.61	0.01	0.12	0.40	10.03	0.79	0.06	0.53	**<0.01**	9.56	0.86	0.04	0.51	**<0.01**	9.18	0.59	0.03	0.31	**0.02**
T_{max}	14.85	0.62	<0.01	0.02	0.89	15.89	0.99	0.08	0.43	**<0.01**	15.39	0.98	0.04	0.43	**<0.01**	14.99	0.72	0.03	0.24	0.07
T_{min}	3.61	0.69	0.03	0.19	0.16	4.71	0.72	0.06	0.54	**<0.01**	4.18	0.89	0.04	0.55	**<0.01**	3.82	0.65	0.03	0.27	**0.04**
GST$_{\text{avg}}$	14.42	0.57	−0.01	−0.10	0.45	15.56	0.68	0.05	0.48	**<0.01**	15.01	0.85	0.04	0.50	**<0.01**	14.64	0.62	0.02	0.23	0.07
GST$_{\text{max}}$	20.99	0.66	−0.02	−0.13	0.35	21.96	0.90	0.06	0.40	**<0.01**	21.50	0.93	0.03	0.39	**<0.01**	21.14	0.70	0.01	0.08	0.57
GST$_{\text{min}}$	8.29	0.66	−0.01	−0.08	0.57	9.62	0.60	0.05	0.52	**<0.01**	8.98	0.92	0.04	0.55	**<0.01**	8.61	0.74	0.03	0.23	0.09
P	1160	155.2	−2.45	−0.07	0.59	1114	135.9	−0.77	−0.08	0.57	1136	146.0	−1.28	−0.11	0.24	1146	159.7	−0.01	<0.01	1.00
GSP	795	126.4	−2.53	−0.11	0.42	776	118.6	0.02	<0.01	1.00	785	121.7	−0.73	−0.07	0.42	784	124.3	0.53	0.03	0.83
HI	1675	99.0	−1.18	−0.07	0.59	1870	165.4	10.15	0.38	**<0.01**	1776	167.8	6.15	0.46	**<0.01**	1704	111.0	3.04	0.17	0.19
GDD	1080	95.8	−0.86	−0.03	0.83	1282	132.7	8.53	0.46	**<0.01**	1184	153.9	6.50	0.51	**<0.01**	1113	106.0	5.16	0.27	**0.04**
NDT$_{\text{max30}}$	8.29	5.54	−0.06	−0.08	0.59	16.27	11.05	0.55	0.38	**<0.01**	12.41	9.64	0.23	0.34	**<0.01**	8.63	4.62	−0.03	−0.06	0.68
NDGS	159	22.09	0.50	0.12	0.95	184	17.24	0.80	0.30	**0.02**	172	23.07	0.86	0.42	**<0.01**	168	20.18	0.06	0.01	0.94
Maribor																				
T_{avg}	9.50	0.60	0.02	0.19	0.17	10.55	0.82	0.06	0.48	**<0.01**	10.03	0.89	0.04	0.52	**<0.01**	9.70	0.59	0.03	0.37	**<0.01**
T_{max}	14.71	0.67	−0.01	−0.06	0.67	15.61	1.01	0.07	0.37	**0.03**	15.16	0.96	0.03	0.34	**<0.01**	14.76	0.74	0.03	0.25	0.06
T_{min}	4.78	0.74	0.06	0.44	**<0.01**	6.21	0.70	0.06	0.52	**<0.01**	5.50	1.02	0.05	0.67	**<0.01**	5.25	0.62	0.05	0.46	**<0.01**
GST$_{\text{avg}}$	14.94	0.53	−0.01	−0.10	0.45	16.13	0.77	0.06	0.49	**<0.01**	15.54	0.89	0.04	0.50	**<0.01**	15.18	0.60	0.02	0.17	0.19
GST$_{\text{max}}$	20.73	0.67	−0.03	−0.31	**0.02**	21.66	0.95	0.06	0.39	**<0.01**	21.19	0.94	0.03	0.31	**<0.01**	20.79	0.72	0.01	0.07	0.62
GST$_{\text{min}}$	9.64	0.54	0.03	0.32	**0.01**	11.27	0.66	0.05	0.53	**<0.01**	10.45	1.01	0.05	0.68	**<0.01**	10.17	0.65	0.04	0.35	**0.01**
P	1047	148.9	−3.81	−0.13	0.34	1021	126.9	−3.38	−0.14	0.30	1034	137.7	−1.59	−0.13	0.16	1046	147.2	0.33	0.01	0.97
GSP	724	116.9	−1.19	−0.05	0.69	724	110.9	−0.43	−0.05	0.73	724	113.0	−0.42	−0.06	0.51	725	116.5	−0.98	−0.06	0.67
HI	1695	111.5	−2.97	−0.19	0.15	1894	182.1	11.58	0.39	**<0.01**	1795	180.2	5.65	0.41	**<0.01**	1714	118.4	3.08	0.15	0.24
GDD	1167	95.7	−1.17	−0.05	0.72	1390	155.3	10.84	0.48	**<0.01**	1278	170.3	6.78	0.51	**<0.01**	1206	108.0	3.55	0.20	0.12
NDT$_{\text{max30}}$	6.37	5.67	−0.06	−0.09	0.50	13.47	11.39	0.50	0.40	**<0.01**	9.92	9.61	0.17	0.30	**<0.01**	5.83	3.79	<0.01	0.06	0.68
NDGS	175	25.41	1.09	0.25	0.12	210	18.44	0.28	0.09	0.50	192	28.42	1.05	0.46	**<0.01**	194	25.49	0.96	0.24	0.07
Jeruzalem																				
T_{avg}	9.92	0.60	<0.01	0.04	0.82	10.47	0.82	0.05	0.38	**<0.01**	10.22	0.77	0.02	0.32	**0.01**	9.92	0.61	0.02	0.17	0.20
T_{max}	14.09	0.71	0.02	0.08	0.60	14.90	1.14	0.09	0.44	**0.01**	14.54	1.05	0.04	0.36	**<0.01**	14.13	0.77	0.01	0.13	0.34
T_{min}	6.09	0.51	<0.01	0.07	0.67	6.63	0.75	0.05	0.37	**0.04**	6.39	0.70	0.02	0.34	**0.01**	6.13	0.54	<0.01	0.06	0.67
GST$_{\text{avg}}$	15.28	0.57	−0.03	−0.31	**0.04**	15.95	0.72	0.04	0.33	**0.01**	15.65	0.73	0.02	0.31	**0.01**	15.38	0.62	<0.01	−0.01	0.96
GST$_{\text{max}}$	20.02	0.67	−0.02	−0.11	0.47	20.99	1.10	0.08	0.42	**0.01**	20.56	1.05	0.03	0.37	**<0.01**	20.16	0.74	<0.01	−0.02	0.91
GST$_{\text{min}}$	10.86	0.59	−0.02	−0.17	0.26	11.54	0.68	0.04	0.32	0.14	11.24	0.72	0.02	0.35	**<0.01**	11.00	0.65	<0.01	−0.02	0.89
P	969	166.9	−3.65	−0.12	0.41	934	150.6	1.80	0.05	0.69	950	157.5	−0.64	−0.04	0.68	954	167.4	−3.78	−0.17	0.19
GSP	651	134.3	−3.78	−0.17	0.24	647	129.7	1.59	0.06	0.68	648	130.5	−0.49	−0.03	0.77	643	133.1	−2.64	−0.13	0.34
HI	1649	101.2	−4.75	−0.15	0.31	1818	181.3	10.56	0.37	**<0.01**	1743	172.1	5.61	0.38	**<0.01**	1671	117.2	0.95	0.04	0.75
GDD	1231	102.6	−6.46	−0.21	0.16	1364	143.6	6.76	0.26	**0.04**	1305	142.6	3.90	0.33	**<0.01**	1249	111.8	0.69	0.05	0.72
NDT$_{\text{max30}}$	2.67	2.53	−0.06	−0.27	0.09	9.23	9.11	0.39	0.38	**<0.01**	6.31	7.68	0.15	0.33	**<0.01**	3.10	3.40	<0.01	0.01	0.96
NDGS	213	20	−1.34	−0.30	**0.03**	211	21.40	0.30	0.09	0.49	212	20.48	−0.17	−0.09	0.35	212	22.66	−0.89	−0.21	0.10

number of days with temperature >30°C being 9, 13, and 16 for Jeruzalem, Maribor, and Celje, respectively (Table 2). Too many days with temperatures >30°C can induce a reduction in photosynthesis and cause premature ripening, especially in early-ripening varieties (Vršič &Vodovnik-Plevnik 2012).

The warming trends during the period between 1980 and 2009 were confirmed by the increase of heat summation indices and by the average annual and growing-season temperatures. These have obviously been influenced by the number of days with maximum temperatures >30°C (NDT_{max30}). GDDs and the HI increased at all stations during the period 1980–2009. GDDs increased from 68°D units in Jeruzalem, and 85°D units in Celje to 108°D units decade^{-1} in Maribor. The GDD trends were more pronounced at the Maribor and Jeruzalem locations than at Celje.

The HI trends were similar to those for the GDD. HI values for the stations were from 169 (Jeruzalem) to 199°D units (Maribor) higher during 1980–2009 than during the period between 1950 and 1979 (Fig. 2). These values identify the Slovenian Styria as suitable for Chardonnay and Sauvignon Blanc on the HI. Similar results were reported by Duchêne & Schneider (2005) for Alsace, Germany. During the first decade (1980–1989) of this period, HI exceeded the value of 1900°D units only once, while in the third decade (2000–2009) it exceeded the value 8 times (during 3 yr it was >2100°D units).

Regarding the arrangement of wine-growing areas into climate-maturity groupings (Jones 2006, Jones et al. 2010) based on GST_{avg} increases in the last decade of the examined period, it can be assumed that this wine-growing region has become suitable for the cultivation of some wine varieties from the warm-climatic maturity group, such as Cabernet Franc, Merlot, and Cabernet Sauvignon. If the warming trend continues over the next 30 yr in a similar way as it has since the 1980s, it can be expected that the Slovenian Styria wine-growing region may proceed completely into the warm-climatic maturity group.

In general, the precipitation amounts for the whole period (1950–2009) decreased slightly; however, the trends in annual (*P*) and growing-season precipitation (GSP) were not significant (Table 2). The rainfall averages were more or less stable at all locations. However, drier conditions, with more frequent and longer periods of drought, were more likely because higher temperatures probably resulted in a higher rate of evapotranspiration.

3.2. Climate change and grapevine growth

The harvest date moved forward for all varieties (Fig. 3). Trends for Welschriesling, Muscat Blanc and Pinot Gris were similar and showed an earlier maturity by 21, 22 and 25 d, respectively. The harvest date shifted from mid-October to mid-September for Muscat Blanc and Welschriesling, and from the first week of October to the first week of September for Pinot Gris. For the late-ripening varieties the extremes were similar, but for Muscat Blanc they were more pronounced than for Riesling. In the dry years (2000, 2003, and 2007), the harvest dates of Muscat Blanc fell within the last decade of August (in 2003 in mid-August), which is a common harvest period for an early-ripening variety in this region. In the dry years the content of aromatic substances is usually lower, especially the primary aromas typical of the variety, and herbal aromas dominate. The number of so-called 'poor vintages' (below appropriate sugar content) characteristic for the Muscat Blanc in the 1980s was considerably reduced. The harvest date of

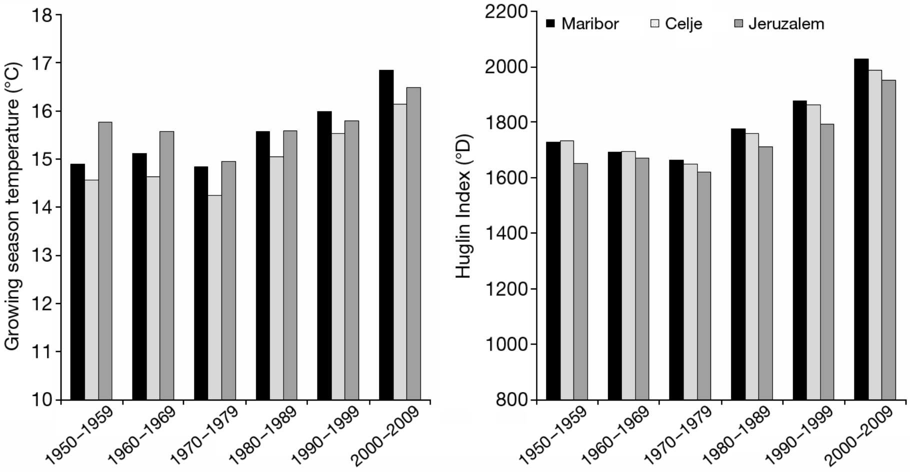

Fig. 2. Mean growing-season temperature and Huglin Index by decades in Celje (1952–2009), Maribor (1950–2009) and Jeruzalem (1956–2009) in the Styrian wine-growing region of Slovenia

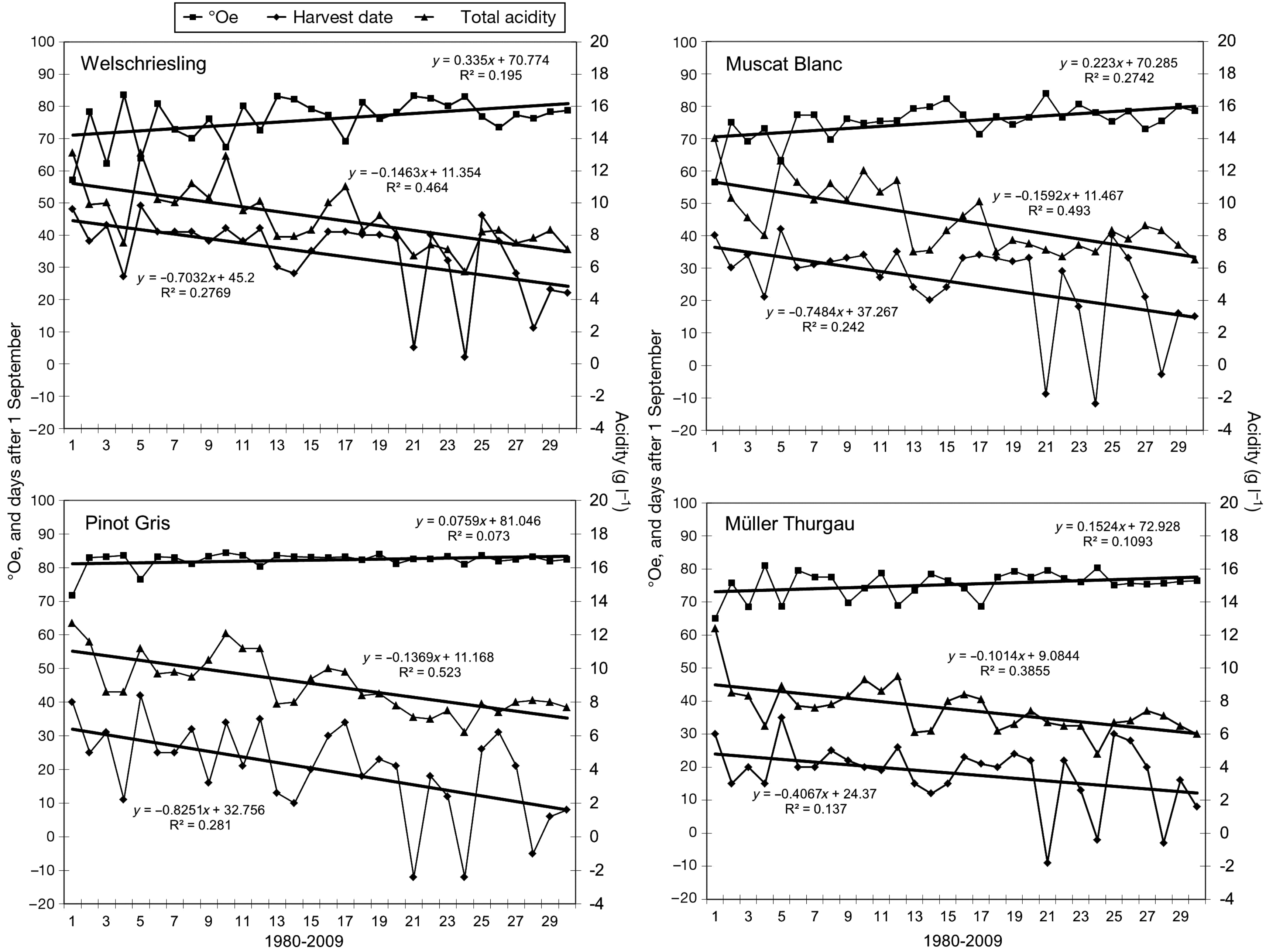

Fig. 3. Trends showing the shortening of the growing season until the recommended harvest date (content of soluble solids in °Oe) and decreasing content of total acidity in grape juice of the late-ripening varieties Italian Riesling and Muscat Blanc, medium- to late-ripening variety Pinot Gris, and early-ripening Müller Thurgau in the sub-wine region Maribor (Slovenian Styria) for the period 1980–2009

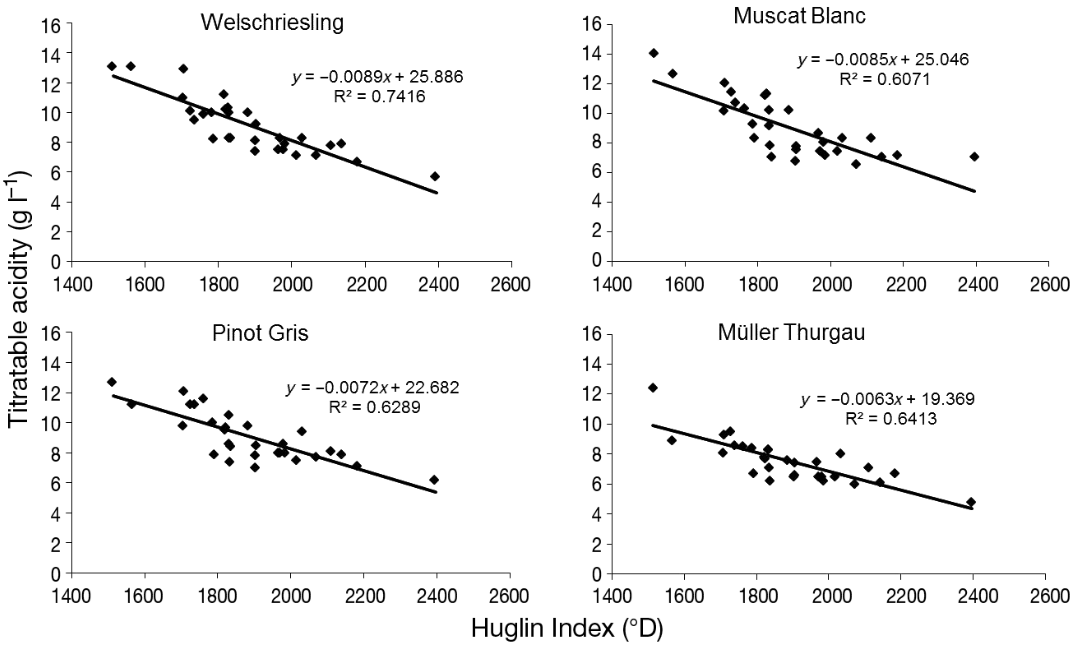

Fig. 4. Linear regressions between total acidity content and the Huglin Index for 4 wine varieties in the sub-region of Maribor (Slovenian Styria) for the period 1980–2009

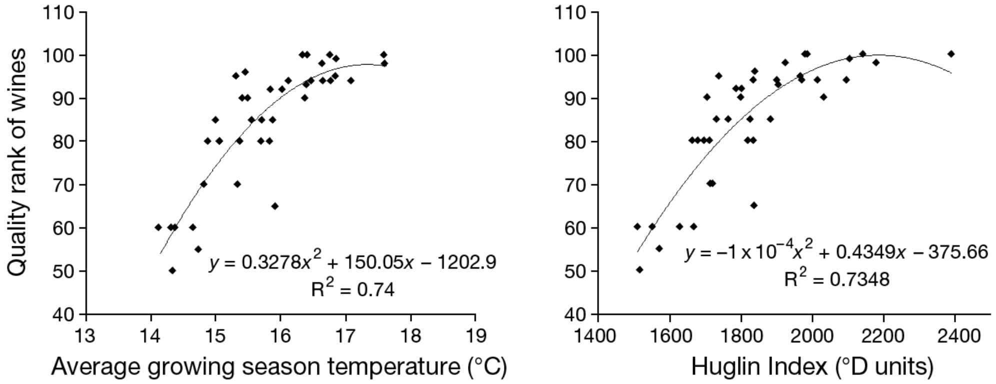

Fig. 5. Quadratic regressions between the Huglin Index and average growing-season temperature and quality rank of wines in Slovenian Styrian for 1970–2009

Müller Thurgau shifted from the last to the second week of September. In the last 10 yr, the grapes of Müller Thurgau ripened very early, especially in 2000 and 2003, but extremes were not as pronounced as they were in other varieties. In dry years, it ripened in the last week of August. The trends to earlier maturity were stronger after 2000.

Despite earlier grape ripening, reduced total acidity can result from higher temperatures and evapotranspiration, and lower water supply to the vine during the time from growth of the berries to grape ripening. In Muscat Blanc, total acidity decreased from 11 g l^{-1} at the beginning of the 1980s to 6 g l^{-1} in 2009. In the other varieties, the reduction was from 3 to 4.5 g l^{-1}, and the total acidity content was around 6–7 g l^{-1} (Fig. 3). Total acidity for late-ripening varieties approached optimal values. In the early-ripening varieties, acidity was around the desired level, and lower in dry years. Thus, the increase in temperatures during grape ripening influences the chemical composition of grape must. The content of malic acid decreased for the most part. In cool climate regions some reduction in acid might produce a better sugar/acid balance, while in early-ripening varieties, the loss of acid might result in flabby wines without acidulation in the winery (the same as in warmer regions). A warmer growing season results in an earlier harvest date and lower production, as well as improved wine quality and vintage rating (Jones et al. 2005, Ramos et al. 2008, Webb et al. 2012).

All varieties showed a strong correlation ($p < 0.01$) between total acidity and HI (Fig. 4). At the beginning of the 1980s, the early- and medium- to late-ripening varieties usually reached the appropriate sugar content, but the late-ripening varieties did not (Fig. 3). The quality rank increased significantly and the dependence of GST_{avg} values and the HI can be seen in quadratic models (Fig. 5). Excellent vintage ratings (>90 points) are expected above 16°C of GST_{avg} (optimum: 17.3°C) and above 1906 HI (optimum: 2174°D units). During 1970–1990 only 1 vintage was excellent (1983, 100 points), and most of the good vintages occurred in the 1980s. After 1990, most vintages had >90 points; 3 of them were excellent. The evolution of vinicultural practices and the reduction in yield in the past 30 yr has also improved wine quality. However, if the trend in regional warming continues as predicted by climate models (Köhler 2009), or continues at the same rate as it has been occurring in the past 30 yr, the Slovenian Styria wine region will likely see lower quality vintages, mainly because of low acid content, very high alcohol, and other less desirable wine characteristics.

3.3. Conclusions

The results of this study suggest that changes in the climate parameters have not been uniform over the observed time periods. Significant increases in temperature parameters have been identified since 1980 in the studied wine-growing region. Trends indicate an average growing-season warming of 1.5°C. Similar trends have been observed in other European and in the world's best wine-growing regions (Jones et al. 2005). According to the established trends in GST_{avg}, the Slovenian Styria wine region is placed today alongside the Rhine and Loire Valleys and Burgundy.

Estimation of the impact of climate change on the growth cycle of the grapevine has shown a significant impact on harvest timing and season duration. In this research grape maturity occurred 4–8 d decade^{-1} earlier for all varieties studied, and harvest was advanced into a warmer part of the season. The ripening of grapes in the region occurred under warmer conditions, and trends since the 1980s have indicated a decrease in the total acidity content. The decline in total acidity content exhibited a strong correlation with the HI ($r > -0.6$ for all varieties), which, combined with higher sugar contents, would mean potentially less balanced wines.

In general, the quality of wine increased after 1970. Even if higher temperatures lead to better wine quality, continuous increases in temperature could, in the long run, result in changes to the quality of the wine produced in this region. More negative influences of climate change can be expected in the case of early-ripening and aromatic varieties (lower acid, bitter substances, and atypical aromas and wine aging, etc.). For the late-ripening varieties (Muscat Blanc and Welschriesling), climate change has a positive effect on grape ripening, but potential changes in the style of wine can be observed for most of varieties. One potential adaptation is that early varieties can be grown on more northerly facing slopes with less insolation. In this wine region, such a change would be possible because the majority of vineyards are on steep slopes with different sun exposures.

In both the past and present, all wine regions in NE Slovenia have been well suited to quality white wine production. However, major changes are expected if warming trends continue to the same extent as noted in the 1980–2009 period examined in this research. In Slovenia, the demand for fresher and younger wines is increasing. Therefore, wine-growing areas where vines are grown on steep slopes have a greater ability to customize the style of wine according to those trends. While Slovenian wine quality has improved in the past 3 decades due to climate, it has also improved due to modernization in both the vineyard and winery. Consideration of climate change impacts on vine phenology will allow determination of some of the adaptive strategies that could be useful in planning future vineyard development. It will therefore be necessary to adapt cultural practices, especially the technique of arrangement and care of vineyards (Vršič et al. 2011). A more long-term measure is the replacement of varieties, because the wine laws allow the planting of only certain varieties in certain regions of Europe. Therefore, the use of drought-tolerant rootstocks is a reasonable adaptation.

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