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Potential climate change impacts on winegrape must density and titratable acidity in southwest Germany

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ABSTRACT: This research presents estimations for the development of must density and titratable acidity of wine produced during the 21st century in the federal state of Baden-Wuerttemberg in southwestern Germany. The estimations were based on 30 yr long records of climate data and vintages which were then used to initialize a statistical model. The results of the statistical model were used to estimate the must density and titratable acidity of future vintages based on data from climate simulation runs from 2 regional climate models: the regional climate model REMO with A1B and A2 emission scenarios and the climate version of the local model (CLM) with the A1B emission scenario. The estimation was made for the 30 yr periods 2011–2040, 2041–2070 and 2071–2100. An increase of must density and a decrease in titratable acidity for the viticultural districts of Baden and Wuerttemberg as well as for the Bodensee area were detected. The increase in must density from one 30 yr period to the next ranged from 4 to 7° Oechsle, and the decrease in titratable acidity ranged from 0.5 to 2 g l^{-1}. Changes of these magnitudes likely will endanger the quality of established brands without appropriate grower and winemaker adaptations. The results of this study provide a detailed description of possible forthcoming climate-driven impacts on must density and titratable acidity values which can assist viticulturalists in planning adaptations to those changes.

KEY WORDS: Viticulture · Southwestern Germany · REMO · CLM · Must density · Titratable acidity

1. INTRODUCTION

Viticulture is closely connected with local climate conditions such that historical viticulture dates have been used to reconstruct long-term weather data timelines (Meier et al. 2007, Brázdil et al. 2008, Mariani et al. 2009, Krieger et al. 2011). The effects of recent climate change on viticulture have already been observed in some regions of the world. In France and Germany, an extension of the growing season has been detected over the last several decades, and the phenology of grapevines has shown a tendency towards earlier events (Jones & Davis 2000, Duchêne & Schneider 2005, Bock et al. 2011). Climate variations and trends were found to influence vintage quality ratings, with up to 60% explained by growing season temperature variations which had the greatest effects in the cooler climate regions of the Mosel and Rhine valleys of Germany (Jones et al. 2005). Additionally, an early water deficit was found to promote an increase in berry sugar and a reduction in acidity (van Leeuwen et al. 2004).

Nevertheless, the quantity and quality of the winegrapes during harvest do not depend entirely on climate factors. Viticulturalists can influence the ripening potential to a significant degree (Becker & Steinmetz 2005). By applying cultivation techniques such as defoliation, cluster thinning and shoot thinning, they can markedly affect yield components such as berry weight, and wine characteristics such as must density and acidity (Reynolds 1989, Dami et al. 2006, Kok 2011, Gatti et al. 2012, Sun et al. 2012).

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Local climate conditions and variations essentially set the boundaries for decisions that viticulturalist make to potentially improve the quantity and quality of their grapes. Even harvest dates, which are known as 'false phenological phases', show high correlations with air temperature (Menzel et al. 2006). Viticulturalists presumably make every effort to use up-to-date cultivation techniques to achieve high levels of efficiency and good product quality, but baseline climate conditions and variabilities remain the most unpredictable factors in their operations.

Estimations of wine characteristics have been made with climate conditions as input values while knowing the limitations of such estimations. These estimations commonly include the must density and acidity and in Germany are often recorded in degrees Oechsle (°Oe), ‰ or g l^{-1}. For instance, must density and titratable acidity of white wines of the Upper Moselle region were found to be significantly influenced by air temperatures in research conducted by Urhausen et al. (2011). The average uncertainty of the model was around 3°Oe for must density and less than 1 g l^{-1} for titratable acidity. Another study for the estimation of must density was conducted by Löhnertz et al. (2004) for the Rheingau area in west-central Germany. Meteorological data as well as information about soil and topography were used for the calculation. The differences between estimated and actual must density ranged from 5 to −5°Oe. In their research of 3 grapevine varieties in Austria, Mehofer et al. (2005) found significant linear relationships between an increase of air temperature sums and sunshine durations (SDs) with an increase in must density and a decrease in titratable acidity.

The high correlation between climate conditions and wine characteristics shows that climate change has the potential to impact viticulture to a great extent. A 5-member, high resolution model ensemble using the Special Report on Emissions Scenarios (SRES) A1B scenario (IPCC 2007) simulated a mean air temperature increase of 1.1 K over Germany (0.9 K in summer) by 2050, while the mean precipitation increased by 3 % but with a decrease in wet days in summer (Wagner et al. 2013). In an examination of multiple viticultural climate indices, Malheiro et al. (2010) expect western and central European regions to benefit from future climate conditions with higher wine quality and new potential areas for viticulture for the 21st century. For the viticultural districts of Baden and Wuerttemberg in southwestern Germany, Neumann & Matzarakis (2011) detected an increase in Huglin Index (HI) values during the 21st century with simulation runs of 3 regional climate models (RCM). This increase resulted in an expansion of areas that are potentially suitable for viticulture as well as a change in the optimal grape varieties for the present areas. As a result, it might be difficult to keep the current standard of high quality wines with current varieties. The expected rise in atmospheric CO_2, which is one driver of climate change, may be an advantage for viticulture. An increased CO_2 concentration was shown to stimulate grapevine photosynthesis and yield (Moutinho-Pereira et al. 2009). A study by Bindi et al. (2001) demonstrated a significant increasing effect on biomass components by rising CO_2 levels but no lasting effect on sugar or acidity levels. They concluded that the rise in CO_2 would increase grapevine production without a significant effect on fruit or wine quality. A survey by Battaglini et al. (2009) showed that viticulturalists were becoming more and more aware of climate-driven changes and their potential impacts.

The current study is the last part of a series of 3 studies. In the first study, a statistical model (STM) was developed and evaluated to estimate must densities and titratable acidity values in Baden-Wuerttemberg based on the HI (Neumann & Matzarakis 2014a). In Neumann & Matzarakis (2013), the model was improved by adding the climatic water balance (CWB) and the SD. The aim of the current study was to apply the previously developed STM using data from climate simulation runs. This was done to produce the first quantitative estimation of the possible future development of must density and titratable acidity of wines from Baden-Wuerttemberg during the 21st century under changing climate conditions.

2. DATA

2.1. Weather stations

Data observed from 11 weather stations were used for initialization of the STM applied in this research. All stations are run by the German Weather Service (DWD) and are located in or near viticultural districts in Baden-Wuerttemberg (Fig. 1, Table 1). For a regression analysis with must density data, records of 1981–2010 were used, and for a regression analysis with titratable acidity data, records of 1973–2002 were used. It was necessary to distinguish between the periods of 1981–2010 and 1973–2002 because of a lack of titratable acidity records, which is explained below. An overview of the available data can be seen in Table 1. The meteorological data used consisted of

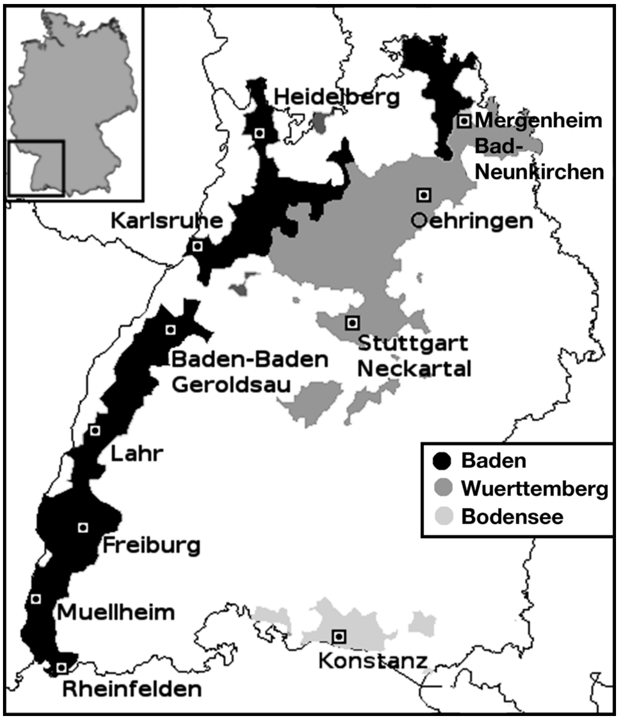

Fig. 1. Weather stations and viticultural districts (Statistisches Landesamt Baden-Wuerttemberg 2009)

the mean air temperature, maximum air temperature, minimum air temperature, SD, average wind speed, average air pressure, average vapor pressure and precipitation, all available in daily resolution.

2.2. Viticultural districts

The viticultural areas in Baden-Wuerttemberg are divided into 2 districts: Baden and Wuerttemberg. Most of the Baden district is located in the Rhine Valley, while most of the Wuerttemberg district is located in northeastern Baden-Wuerttemberg (Fig. 1). The area around the Bodensee is a special case since it is clearly separated from the other 2 viticultural districts. Therefore, we made a distinction between Baden and Wuerttemberg and the Bodensee area and considered them as separate districts. The number of weather stations located in the districts of Baden, Wuerttemberg and Bodensee are 7, 3 and 1, respectively (Table 1).

2.3. Records of wine characteristics

Records of wine characteristics recorded by the statistical office of the federal state of Baden-Wuerttemberg (SLBW) were used as initialization parameters for the STM. The records were based on voluntary reports from viticulturalists. Data about annual must density and acidity attained from fruit as measured when they arrive into the winery after harvest were available as averages in units of °Oe and ‰. The °Oe is the unit used in Germany for the ratio of soluble solids in grape must with sugar as the main part. For the purpose of this work, g l^{-1} was used as the unit for titratable acidity instead of ‰. The datasets used did

Table 1. Weather stations, assignment of each station to a viticultural district and available data to calculate the Huglin Index (HI), climatic water balance (CWB) and sunshine duration (SD)

Station (viticultural district)	Latitude (°)	Longitude (°)	Elevation (m)	Available data (%) HI and CWB		Available data (%) SD	
				1981–2010	1973–2002	1981–2010	1973–2002
Baden-Baden Geroldsau (Baden)	48.73	8.25	240	100	100	0	0
Freiburg (Baden)	48.02	7.84	236	100	100	100	100
Heidelberg (Baden)	49.42	8.67	110	99	99	22	49
Karlsruhe (Baden)	49.04	8.37	112	93	100	93	100
Lahr (Baden)	48.37	7.83	155	90	90	87	60
Muellheim (Baden)	47.81	7.64	273	91	97	31	58
Rheinfelden (Baden)	47.56	7.79	287	100	100	88	93
Mergentheim, Bad-Neunkirchen (Wuerttemberg)	49.48	9.76	250	100	100	0	0
Oehringen (Wuerttemberg)	49.21	9.52	276	100	100	100	100
Stuttgart (Wuerttemberg)	48.83	9.2	314	100	100	100	84
Konstanz (Bodensee)	47.68	9.19	443	100	100	100	100

not make a distinction between the different grape varieties grown in the region and therefore carried a summary value for the entire harvest in the districts. As stated earlier, records of 1981 through 2010 were used for the regression analysis with must density data, and records of 1973 through 2002 were used for the regression analysis with titratable acidity data. After 2002, the SLBW stopped keeping records of titratable acidity because of an insufficient number of reports from the viticulturalists. The average must density in 1981–2010 was 78°Oe and ranged between 68 and 93°Oe. The average titratable acidity in 1973–2002 was 9.1 g l^{-1} and ranged between 7.6 and 12.0 g l^{-1}.

2.4. RCM data

Data from scenario runs computed by 2 RCM were used for the estimation of forthcoming climate-driven impacts on must density and titratable acidity values. The RCM were forced by the global coupled atmospheric-ocean model ECHAM5/MPIOM (Marsland et al. 2003, Hagemann et al. 2005, Roeckner et al. 2006). The RCM are described as follows.

The 3-dimensional hydrostatic RCM (REMO) was developed by the Max Planck Institute for Meteorology (Jacob & Podzun 1997, Jacob et al. 2007). It is an atmospheric circulation model that calculates the relevant physical processes dynamically. The REMO simulations were chosen because of their focus on covering mainly the area of Germany and the Alps on a regular geographical grid with 0.1° horizontal resolution. The simulation runs used were part of a study of the Federal Environmental Agency (UBA) for the development of regional climate projections (Mahrenholz 2006a,b). Two runs of data stream 3 from 2011 to 2100 were used, one based on the SRES A2 and the other based on the SRES A1B. For the study, the simulation runs were divided into 3 time spans: T1, 2011–2040; T2, 2041–2070; and T3, 2071–2100.

The climate version of the local model (CLM) (Steppeler et al. 2003, Will et al. 2006) was developed by the Consortium for Small-scale Modeling. It is a non-hydrostatic regional model which also calculates the relevant physical processes dynamically. The simulation run was calculated by the Max Planck Institute for Meteorology in Hamburg. The CLM covered mainly the area of Europe and provides simulations with high resolutions for the research area, which were processed for this study in the same manner as the simulations of the REMO model. The CLM simulations used are part of data stream 3 with a non-rotated grid with 0.2° spatial resolution (Lautenschlager et al. 2009). For this study, the time span from 2011 to 2100 based on the SRES A1B was also separated into the time spans T1, T2 and T3.

3. METHODS

3.1. Indices

The STM for the estimation of must density and titratable acidity makes use of 3 climatic indices. The first index is HI, one of the most commonly applied indicators in identifying suitable grapevine varieties for regions in Europe (Huglin 1978). It is a heat summation method combined with a day length factor. The equation used to calculate the HI is:

$$\mathrm{HI} = \sum_{01.04.}^{30.09.} \frac{[(T_{\mathrm{mean}} - 10) + (T_{\mathrm{max}} - 10)]}{2} \times d \qquad (1)$$

where T_{mean} is the daily mean air temperature, T_{max} is the daily maximum air temperature and d is a length of day coefficient with a value in Baden-Wuerttemberg of 1.05 until the 48° latitude and 1.06 for higher latitudes. The HI is calculated from 1 April to 30 September each year, which covers the growing period for winegrapes in most of Europe.

The CWB is the difference in precipitation minus reference crop evapotranspiration (ET_0). The ET_0 was calculated using the guideline of the Food and Agriculture Organization of the United Nations (FAO) (Allen et al. 1998). The CWB represents the water supply with only meteorological data as variables. The CWB values were added over a time span for each year to form the second index. The daily SD in hours were added over a time span for each year to form the third index SD. For the estimation of must density, the time spans used to sum the indices were determined by the STM. For the estimation of titratable acidity, the time span used for all indices ranged from 1 April to 30 September.

3.2. STM

The STM calculates regression equations usable for the estimation of must density and titratable acidity values by calculating correlations between records of vintages and records of observed data from weather stations (Neumann & Matzarakis 2013, 2014a,b). It uses the 3 defined indices HI, CWB and SD, which are combined using multiple linear regressions. For the estimation of must density, the model also calculates the optimal combination of indices using stepwise multiple linear regressions and the optimal time span to sum daily values to an annual index value for each index. For the estimation of titratable acidity values, all indices with a significant correlation ($p < 0.001$) were combined, and the time span was fixed from 1 April to 30 September. This approach produced the best results in the evaluation of the STM (Neumann & Matzarakis 2014b). The model was able to estimate must density with a bias below 1°Oe absolute value, mean average error (MAE) below 4°Oe and root mean square error (RMSE) below 5°Oe. Titratable acidity was estimated with a bias below 0.1 g l^{-1} absolute value, MAE below 0.7 g l^{-1} and RMSE below 0.9 g l^{-1}. The percentage error of the estimations ranged from 4.51 to 5.28% for must density and from 5.76 to 8.87% for titratable acidity.

4. RESULTS

4.1. STM results

The STM was used to calculate regression equations and time spans for the following estimations based on RCM data. For must density, the time spans which performed best in the regression were chosen. The combinations of the indices were calculated using a stepwise multiple regression (Table 2); they all showed a significant correlation ($p < 0.01$) in the regression analysis. For titratable acidity, a static time span was used from 1 April to 30 September. Here the indices without a significant correlation ($p > 0.01$) were excluded, which left only those with a significant correlation ($p < 0.01$) (Table 2). The STM calculated that an increase in HI and SD and a decrease in CWB led to an increase in must density and a decrease in titratable acidity (Table2).

4.2. Must density

4.2.1. Baden

A constant increase in must density in Baden from 2011 to 2100 was calculated based on the RCM simulation runs (Fig. 2). Only slight differences were visible between the SRES A1B and A2, but lower values were seen for the CLM A1B. The visualizations were realized with bean plots (Kampstra 2008) and the Climate Mapping Tool (Matuschek & Matzarakis 2011). A detailed description of bean plots used in climatology was provided by Muthers & Matzarakis (2010). The spatial distribution displayed higher values in the western portion of Baden (Fig. 3). The average increase from one 30 yr period to the next was roughly 4°Oe, which equals 5.3%, shown as differences in T2-T1 and T3-T2 (Fig. 2). The differences in the REMO simulation decreased over time, especially with the SRES A2. For the CLM A1B runs, the results showed slightly greater differences for T3-T2 compared to T2-T1. The spatial distributions of the differences were not striking and displayed no distinct pattern (Fig. 4).

4.2.2. Wuerttemberg and Bodensee

The model calculated a rise of must density from 2011 to 2100 for Wuerttemberg and Bodensee (Fig. 2). Similar to the results for Baden, the CLM runs showed lower values than the REMO runs. A west–east gradient with higher values in the west is seen in the spatial distribution of the mean must density values, which is also similar to the Baden results but more obvious for the Wuerttemberg district, with a larger west–east extension (Fig. 5). The mean increase in must density values in Wuerttemberg was

Table 2. Initializing parameters and results of the statistical model run. Time span row: non-static (calculated by the model), static: (1 April to 30 September). R^2 rows: coefficients of determination of the regression analysis between must density/titratable acidity with the indices Huglin Index (HI), climatic water balance (CWB) and sunshine duration (SD). Correlation rows: (+) positive correlation, index used for estimation; (–) negative correlation, index used for estimation; (X) index not used for estimation

Parameter	Wine characteristic:	Must density			Titratable acidity		
	Time span:	Non-static (calculated by the model)			Static		
	District:	Baden	Wuerttemberg	Bodensee	Baden	Wuerttemberg	Bodensee
HI R^2		0.59	0.48	0.65	0.59	0.72	0.61
Correlation		+	+	+	–	–	–
CWB R^2		0.48	0.43	0.58	0.12	0.32	0.12
Correlation		X	–	–	X	+	X
SD R^2		0.38	0.31	0.49	0.36	0.43	0.18
Correlation		X	+	X	–	–	X

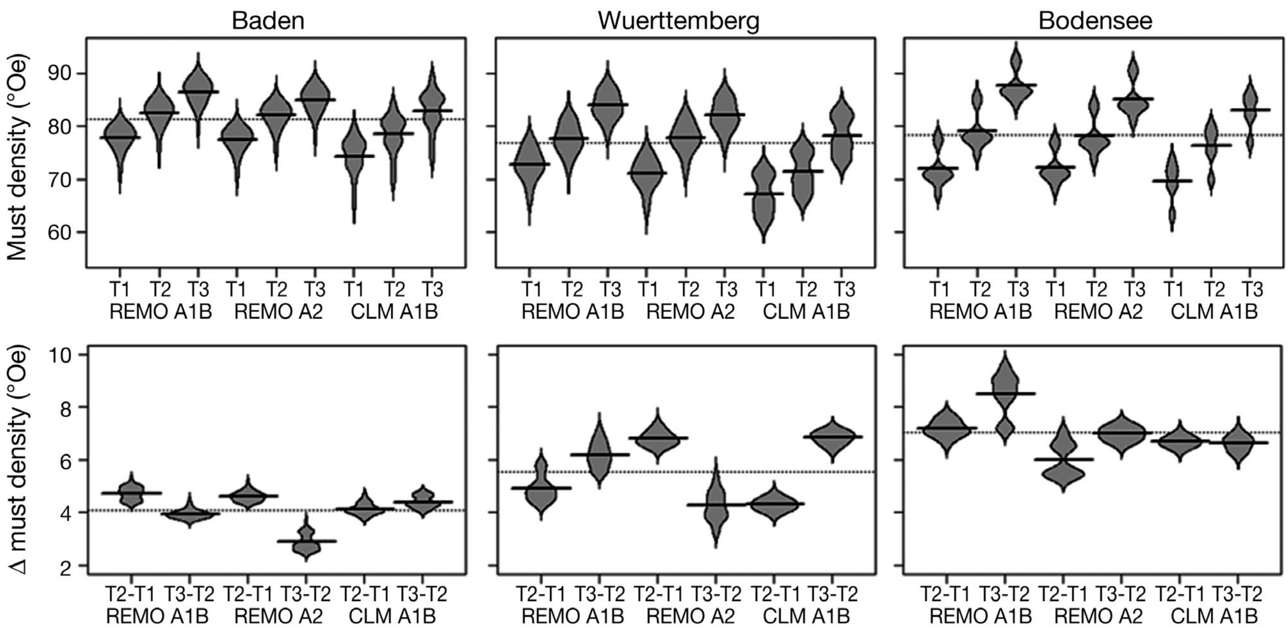

Fig. 2. Mean must density (top) and differences in mean must densities (bottom) of all grid points combined to a bean plot for the 3 viticultural districts for three 30 yr periods. T1: 2011–2040, T2: 2041–2070, T3: 2071–2100. The dotted line marks overall mean. The calculations are based on REMO and CLM data with the emission scenarios A1B and A2

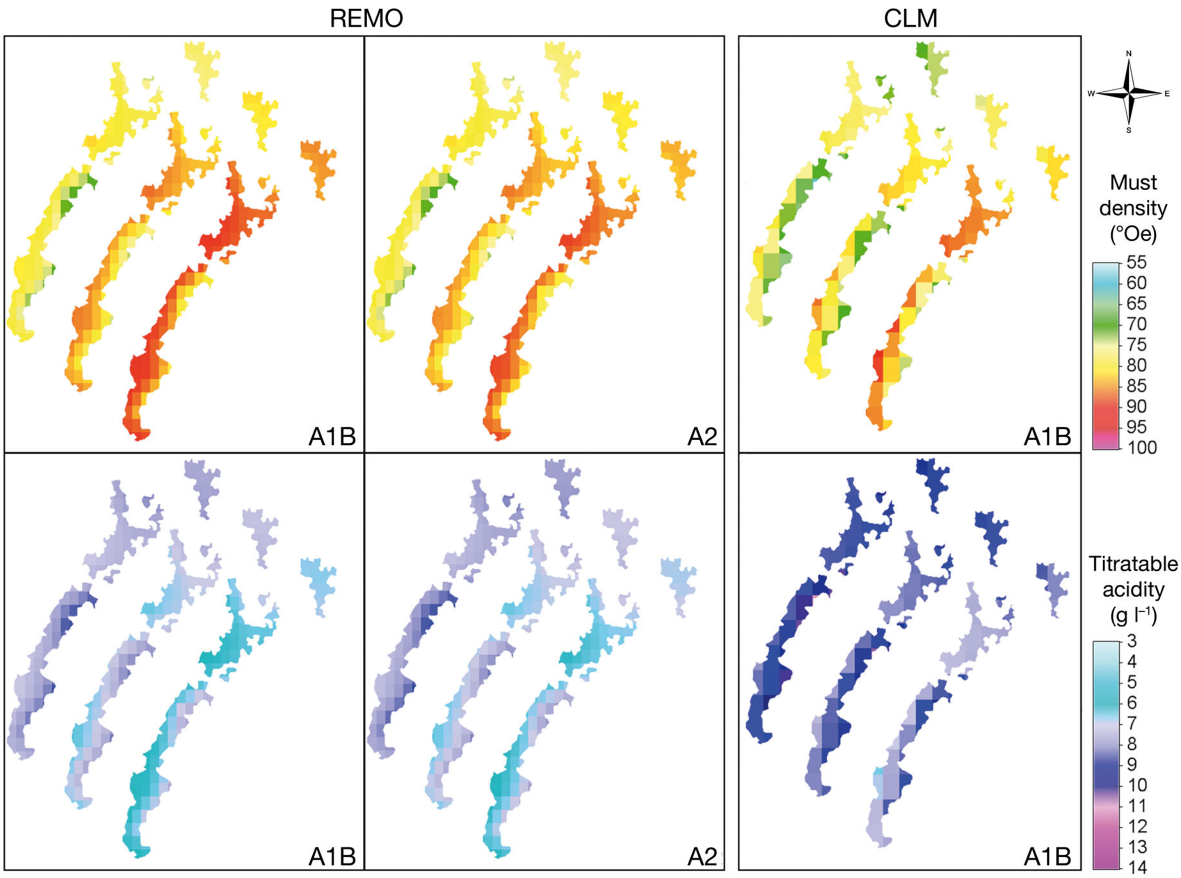

Fig. 3. Mean must density (top) and titratable acidity (bottom) of the 30 yr periods 2011–2040, 2041–2070 and 2071–2100 from left to right for the viticultural district of Baden, Germany. The calculations are based on REMO and CLM data with the emission scenarios A1B and A2

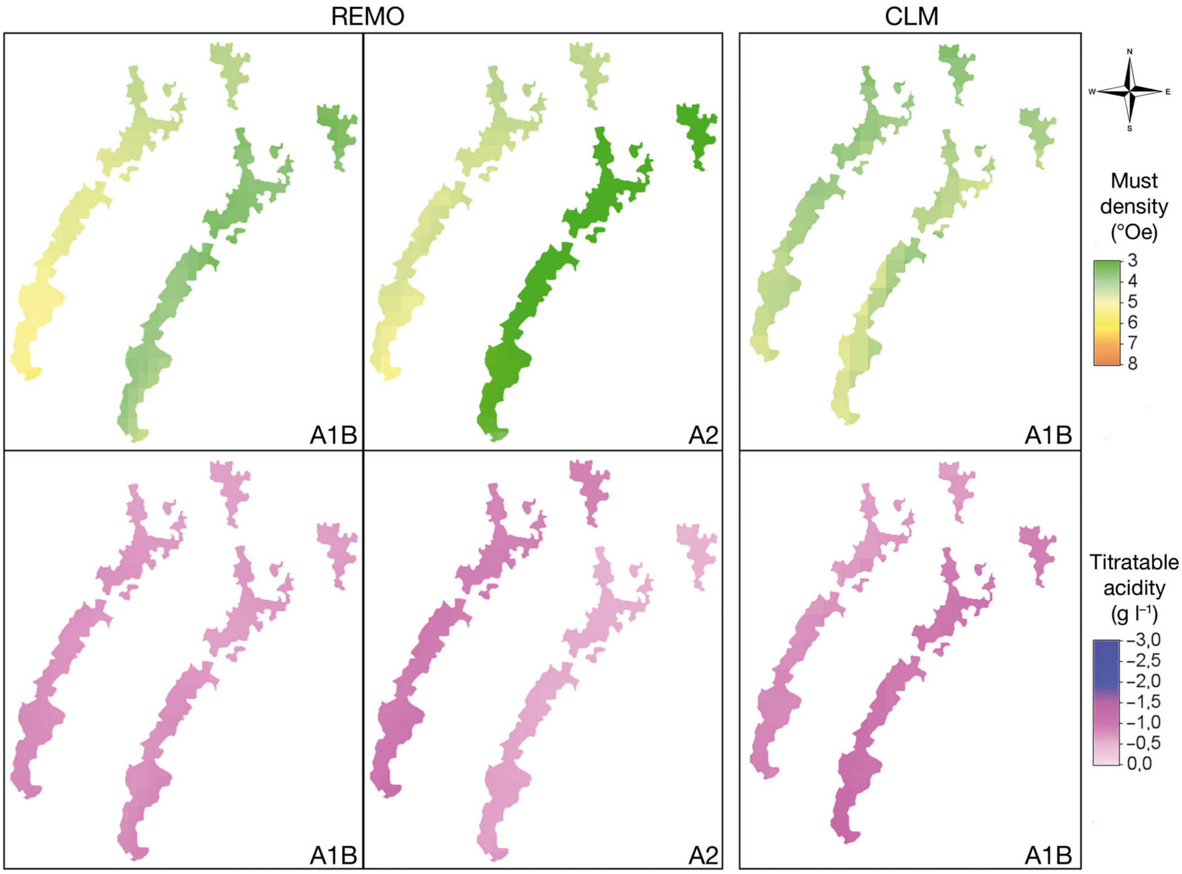

Fig. 4. Differences in mean must densities (top) and titratable acidity (bottom) for the viticultural district of Baden, Germany. Left: 2041–2070 minus 2011–2040, right: 2071–2100 minus 2041–2070. The calculations are based on REMO and CLM data with the emission scenarios A1B and A2

roughly 6°Oe, which equals 7.7%, and was slightly higher in Bodensee, roughly 7°Oe, which equals 9.4% (Fig. 2). The bean plots for Wuerttemberg and Bodensee displayed a wider distribution than the Baden plots (Fig. 2). The bean plot of the differences for Wuerttemberg showed an increase with time for the SRES A1B and a decrease for A2. For Bodensee, the bean plot showed an increase with time for REMO and nearly equal differences for CLM. The spatial distribution of the differences was slightly uneven but with no clear identifiable structure in more than one model or SRES (Fig. 6).

4.3. Titratable acidity

4.3.1. Baden

A decrease in titratable acidity from 2010 to 2100 was calculated based on the RCM simulation runs (Fig. 7). Only slight differences were observed between the SRES A1B and A2. The CLM run produced the highest titratable acidity values. The spatial distribution for Baden showed lower values in the western portion of the district (Fig. 3). The average decrease from one 30 yr period to the next was roughly −0.6 g l^{-1}, which equals 7.4% (Fig. 7). For the SRES A2, the differences decreased over time with respect to A1B, but they were stable or displayed an increase in the CLM run. The spatial distribution of the differences was nearly equal in Baden for both the models and SRES (Fig. 4).

4.3.2. Wuerttemberg and Bodensee

The estimations for titratable acidity based on the RCM simulation runs in Wuerttemberg and Bodensee also showed a decrease from 2011 to 2100 (Fig. 7). The highest values were produced with the CLM run. The spatial distribution displayed lower values in the western parts of the districts for both the

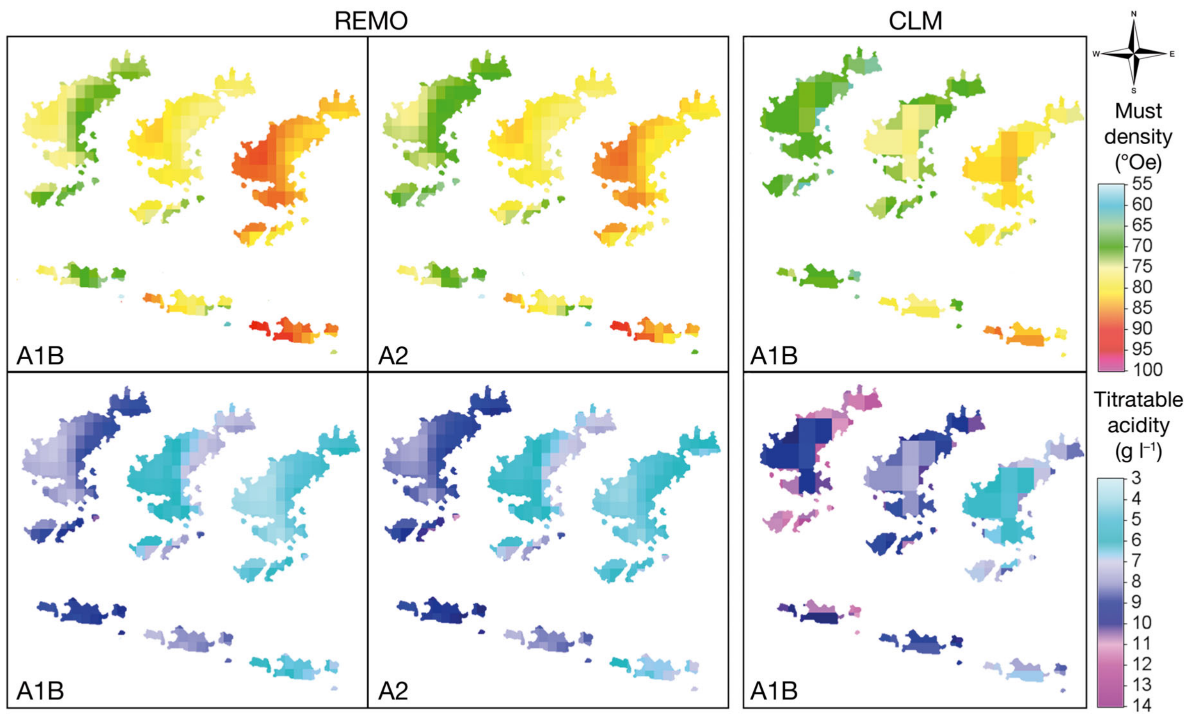

Fig. 5. Mean must density (top) and titratable acidity (bottom) of the 30 yr periods 2011–2040, 2041–2070 and 2071–2100 from left to right for the viticultural districts of Wuerttemberg and Bodensee, Germany. The calculations are based on REMO and CLM data with the emission scenarios A1B and A2

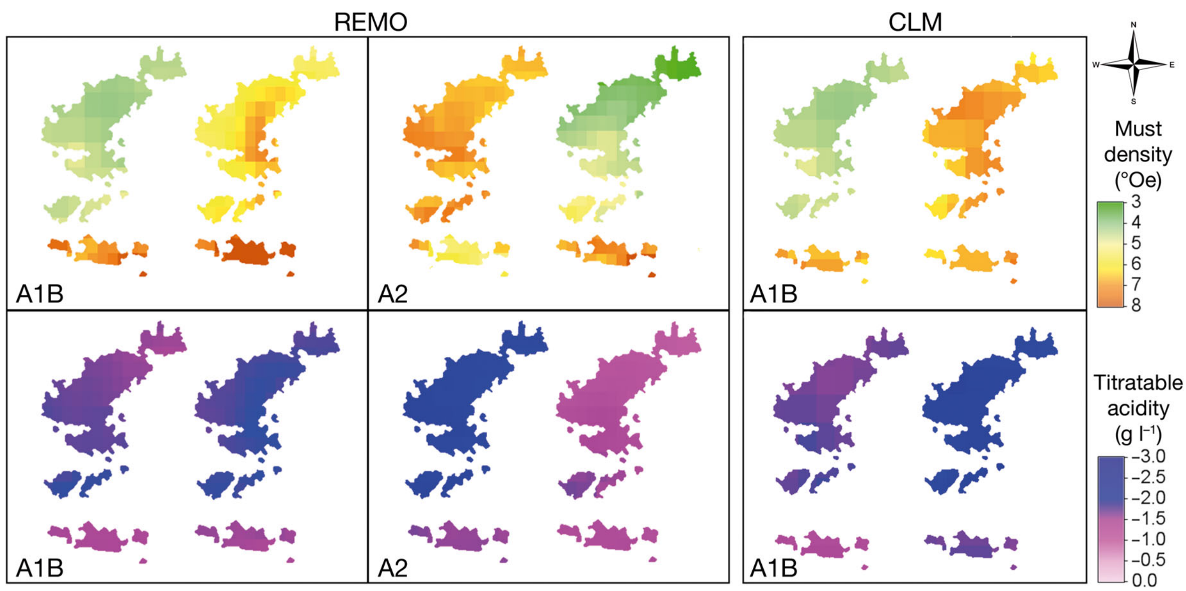

Fig. 6. Differences in mean must densities (top) and titratable acidity (bottom) for the viticultural districts of Wuerttemberg and Bodensee, Germany. Left: 2041–2070 minus 2011–2040, right: 2071–2100 minus 2041–2070. The calculations are based on REMO and CLM data with the emission scenarios A1B and A2

models and SRES (Fig. 5). The mean decrease between the 30 yr periods was roughly −1.8 g l^{-1} for Wuerttemberg, which equals 22.9%, and −1.5 g l^{-1} for Bodensee, which equals 16.9% (Fig. 7). The differences for Wuerttemberg were more distinct compared to those for Bodensee or Baden. For Wuerttemberg and Baden, there was an increase for the 2 A1B runs over time but a decrease for the A2. The spatial distributions of the differences were minor, with slightly larger differences in the south (Fig. 6).

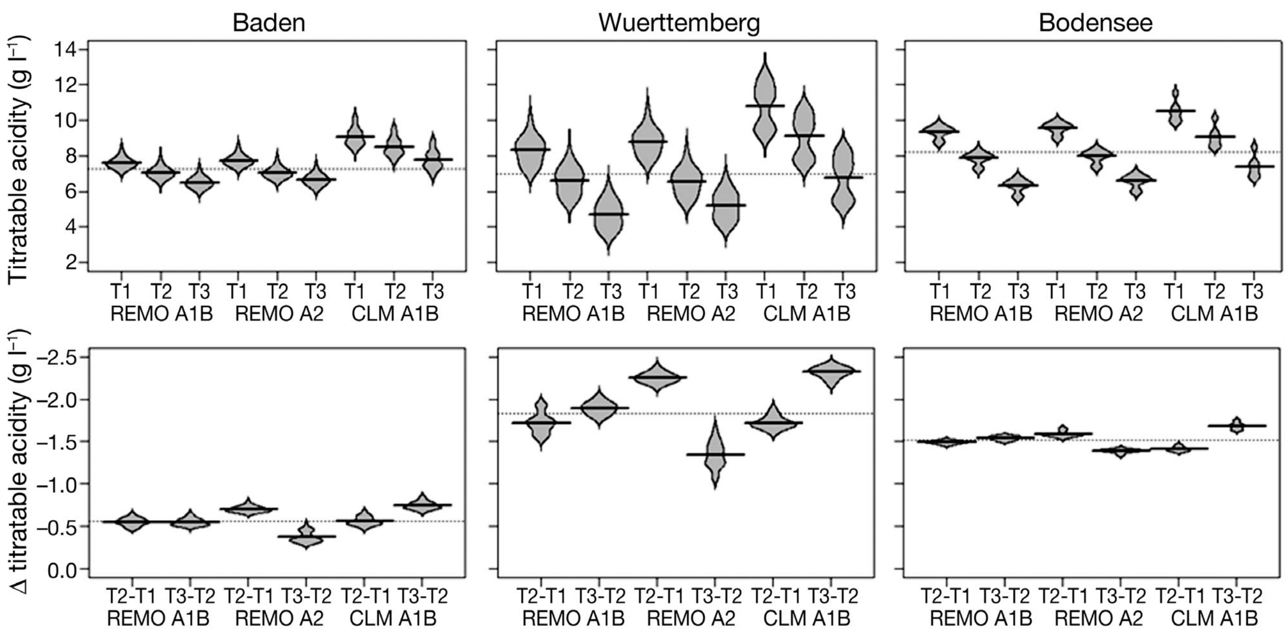

Fig. 7. Mean titratable acidity (top) and differences in mean titratable acidity (bottom) of all grid points combined to a bean plot for the 3 viticultural districts for three 30 yr periods. T1: 2011–2040, T2: 2041–2070, T3: 2071–2100. The dotted line marks overall mean. The calculations are based on REMO and CLM data with the emission scenarios A1B and A2

5. DISCUSSION AND CONCLUSIONS

The increases in must density and decreases in titratable acidity found in this research are similar to those in other studies. For the grape varieties Merlot and Cabernet Sauvignon, Jones & Davis (2000) found large correlations for acid and sugar levels, with floraison and veraison dates that indicate that earlier phenological timing produce higher sugar levels and lower acid ratios. Such trends to earlier phenological timings during the 21st century were simulated for regions in France and Germany for multiple grape varieties by Schultz et al. (2006) and Duchêne et al. (2010). This collection of research points to the effects of an already changing climate on winegrape composition.

This study presents results which provide for the first time a quantitative detailed description of possible forthcoming climate-driven impacts on viticulture in Baden-Wuerttemberg, with the focus on must density and titratable acidity values. This new information should help viticulturalists assess projected climate-driven impacts and plan the proper adaptations to changes in climate in the future. Increases from one 30 yr period to another of roughly 4 to 7°Oe for must density, which equals a change of 5.3 to 9.4%, were estimated together with a decrease of roughly 0.5 to 2 g l^{-1} for titratable acidity, which equals a change of 7.4 to 22.9%. The results of the evaluation of STM in Neumann & Matzarakis (2014b), which applied in this study can be used as an indicator for the error range of the estimation, were briefly summarized in the 'Methods' section.

The STM calculated that an increase in HI and SD and a decrease in CWB led to an increase in must density and a decrease in titratable acidity (Table 2). The effect of the HI and SD increase was expected, as warm and sunny days during the ripening period support the storage of sugar and acid reduction because of the increased energy supply (Vogt & Schruft 2000). The significant correlation found between the CWB decrease and must density increase in Wuerttemberg coincides with a study conducted by Zsófi et al. (2011), in which they related water deficits with higher sugar concentrations mainly because of smaller berry sizes caused by water stress.

Most of the spatial distributions from the modeled sugar and acid surfaces seemed to be a result of different elevations for the grid points, as the spatial distribution followed mainly the topography of the region. The model simulated lower air temperature values at grid points with a higher elevation, which also led to lower must density and higher titratable acidity values. The spatial distribution of the differences was even more in Baden than in Wuerttemberg and Bodensee. This pattern was possibly a result of including the CWB in the calculations for Wuerttemberg and for the must density in Bodensee. Berg et al. (2013) validated different RCM including REMO and CLM. They found a much greater impact of the RCM on precipitation distributions compared to temperature distributions. The different bean plots showed mostly a balanced drop-shaped distribution. The cases that deviated from a drop-shaped distribution were the result of a low number of grid points of the CLM or for the smaller district, Bodensee. The wider range of titratable acidity mean values in Wuerttemberg was possibly related to a higher number of predictive terms, as the CWB was included in the calculations for that district. The estimations with the CLM model showed consistently low must density values and high titratable acidity values compared to the REMO model. This result coincides with a known cold bias of the CLM (Böhm et al. 2006, Jacob et al. 2007, Berg et al. 2013). As seen in Figs. 2 & 7, noticeable differences were found between the T2-T1 and T3-T2 for the SRES A1B and A2 scenarios for Wuerttemberg. These differences were presumably connected with the CWB because the summer precipitation decreased earlier in the 21st century by the SRES A2 compared to A1B in Wuerttemberg (not shown).

In Baden, higher differences for must density were seen by T2-T1 than by T3-T2 (Fig. 2). In these cases, the differences followed the trend of the summer air temperature development (not shown). This decline of the increase in must density values was stronger with the SRES A2 than A1B. This result contradicted the global mean air temperature development expected by the IPCC (2007), where the SRES A2 shows a higher increase to the end of the 21st century than the SRES A1B. The A1B increase rate is expected to decline at the end of the century, which fits with the lower values for T3-T2 by A1B. The lower A2 values can be explained by the results of a regional study conducted by Spekat et al. (2007) using the statistical RCM WETTEG. They found a lower air temperature increase in Baden-Wuerttemberg with the SRES A2 than with the SRES A1B, which showed a regional difference to the expected global mean. Therefore, it can be concluded that a globally higher CO_2 production as a part of the SRES A2 in comparison to A1B does not automatically lead to greater changes in wine characteristics in Baden-Wuerttemberg.

The mean values shown were calculated based on the present conditions. This approach, however, has some disadvantages. First, future changes in cultivation techniques were not taken into consideration. The viticulturalist can still influence the real results in various ways, for example by changing the date of harvest or the grape variety. Titratable acidity can be changed to optimize the finished product (Amann 2006). Since the warm summer of 2003, viticulturalists have been permitted to add acid to the must in warm years. Second, the regression equations were calculated based on local weather station data and then applied to grid points. This approach was used because the weather stations and the grid points were both made to be representative for the local climate. Nevertheless, actual measurements for a station will always be different from the simulated values at a grid point. We therefore focused more on the changes of must density and titratable acidity rather than on actual total values. Nevertheless, an estimation based on a simulation can only provide a detailed trend but not an actual forecast. Despite these limitations, simulation runs of RCM are the most suitable method available today for long-term predictions.

The estimated future changes in wine characteristics can be either positive or negative depending on the viticulturalist and local situation. Viticulture in Germany, one of the most northern wine-producing countries, is mainly done on hillsides to increase insolation and ripening potential. The production of wine on steeply sloped land is more expensive and difficult than on flat ground. Therefore, with a potential increase in must density, viticulture can become more cost-effective and suitable on flatter landscapes. On the downside, traditional German wines are in danger of losing their unique characteristics as the balanced ratio of sugar and acid content shifts in favor of the sugar component (Bock et al. 2011). The changing climate conditions can also influence diseases and pests. For example, an increase in downy mildew is expected in northwestern Italy based on simulations with the SRES A2 (Salinari et al. 2006).

In summary, the ongoing climate change will continue to impact viticulture. Quantitative estimations, such as those performed in this study, can at least provide an estimation of the potential magnitude of these changes. The quality of these estimations could possibly be further improved by combining interdisciplinary research results that include vineyard management decisions, regional economics and cultural identities derived from wine production.

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