



# Changes in phenology and frost risks of *Vitis vinifera* (cv Riesling)

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## Abstract

For a retrospective period of 110 years between 1901 and 2010 (observed data), and for the subsequent future period between 2011 and 2100 we calculated the phenological development (bud burst, harvest ripeness), and in particular the spring frost risk (frost after bud burst), as one important derived variable for grapevine (*Vitis vinifera* L. cv Riesling) for the whole of Germany. For the future climate we included two different scenarios (RCP8.5, RCP2.6) each of them containing a triple set with minimum, medium and maximum temperature increase. The time period between 1981 and 2010 as the last three decades in the observed data was chosen as reference. In general we found an acceleration of the phenological development (all main phases) mainly beginning in the late 1980s. For the three-decade period between 2031 and 2060 this acceleration will reach  $11 \pm 3$  days in the RCP8.5-scenario. The acceleration for the other stages behaved similarly and results in an earlier harvest ripeness of  $13 \pm 1$  days. Since a warmer spring in general leads to earlier bud burst, but does not reduce the risk of frost events during this period in the same manner, changes in the risk of spring frost damage were relatively small. For the coming decades this risk will not decrease for all traditional German viticultural regions in the RCP8.5-scenarios; on the contrary, our results suggest it is likely to increase. The results showed an increasing spring frost risk not only for the debated “upcoming” potential viticultural areas in eastern Germany, an effect which will partly also reach the southernmost viticultural areas. This effect in northern and eastern Germany is due to earlier bud burst together with the stronger continental influence, but for the southern and western regions of Germany is mainly due to the even earlier bud burst. This could modify the regionally nuanced character of German wines.

**Keywords:** climate change, viticulture, phenology, frost risk, Germany, Weinbau

## 1 Introduction

As in many European countries, viticulture in Germany has a long tradition. The earliest traces of cultivation of *Vitis vinifera*, originating from the time of the Romans, have been documented in the well-known Moselle wine region. During the Middle Ages viticulture was also practiced much further north, close to the Baltic coast, being documented in Schwerin around 1228 (LISCH, 1848). During the recent past the regional distribution of German viticultural areas (classified for quality wine production) has remained largely unchanged, with favourable locations in the south and west. But there is increasing interest regarding possible climatic impacts on these traditional German viticultural areas and in the potential expansion of the land area suitable for viticulture. The expansion of viticulture – not only in Germany – has been widely discussed and analysed in a number of studies (BINDI et al., 1996; JONES et al., 2005; SCHULTZ and JONES, 2010) looking not only at the heat demand but also other limiting factors such as frost and

overheating beside other climate impacts on viticulture (WHITE et al., 2006). We will discuss some aspects of these questions for Germany in this paper.

## 2 Material and methods

### 2.1 Climate data

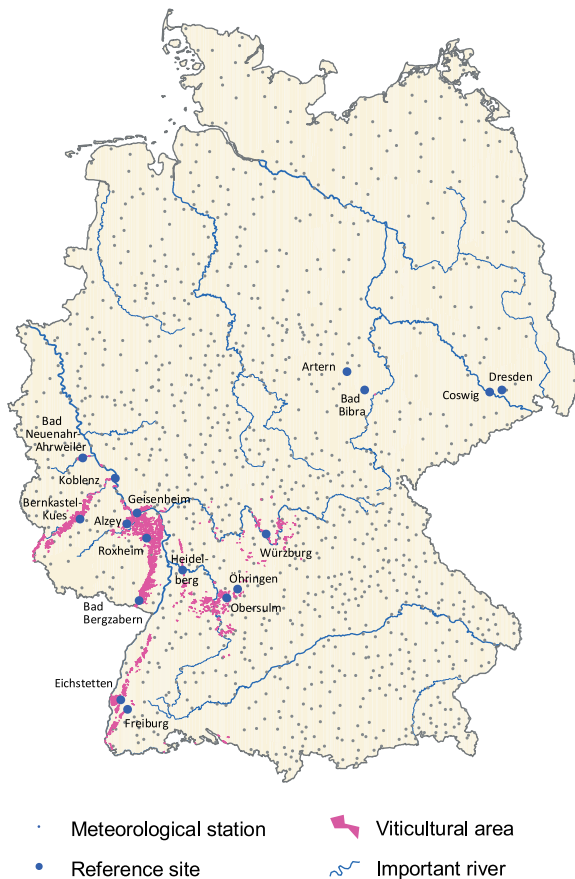
#### 2.1.1 Station-based data

A description of the main data base is given by GERSTENGARBE et al. (2015). Daily data of

$T_{\min}$	minimum of air temperature	[°C];
$T_{\text{mean}}$	mean of air temperature	[°C];
$T_{\max}$	maximum of air temperature	[°C];
$r_H$	mean of relative humidity	[%];
$p_D$	mean of vapor pressure	[hPa];
$P_P$	precipitation sum	[mm];
$v_W$	mean of wind velocity	[m/s];
$Q$	sum of global radiation	[J/cm <sup>2</sup> ]

are available for 180 climate stations and 1038 precipitation recording stations. Station-based calculations for each traditional German viticultural area were based on data from climate stations (Fig. 1), or where there was

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**Figure 1:** Viticultural areas and reference sites of Germany.

no climate station in the area (Baden, Saale-Unstrut, Sachsen and Württemberg), data from a precipitation recording station within or close to the area was supplemented by data from the nearest climate station. A total of 17 stations were selected standing exemplarily for the present German quality wine regions, and also serving for a rough estimate of the accuracy of the interpolation for the high resolution grid data (for details see next section). This enabled a detailed analysis of the 13 German viticultural grape growing areas.

### 2.1.2 High resolution grid data

Beside the station-based data we used a high resolution derivative of the STARS data base (GERSTENGARBE et al., 2015) with a grid size of  $0.055^\circ \times 0.055^\circ$  (approximately  $6.2 \text{ km} \times 3.9 \text{ km}$ ) for the observational period 1901/2010 together with the STARS future scenarios RCP2.6 and RCP8.5 (Moss et al., 2008). The highly non-linear characteristic in the calculation of the grapevine phenology forced the use of an interpolation for the climate input data instead of interpolations of the model outcomes based on the original data (1218 stations). A description of the interpolation algorithm is given by SHEPARD (1968). Because of the high computational effort necessary for the climate data interpolation, phenology calculations were narrowed down to the quantiles q005, q050

and q095 from a set of 100 realizations for all future scenarios. Eventually all grid-based calculations were performed for 16734 grid cells using geographical interpolation to produce daily values of all variables given in section 2.1.1. The grid-based calculated results were mainly used for visualization purposes and to provide a statistical overview.

### 2.1.3 Selection of the reference and comparison periods

The three-decade observational period 1981 to 2010 (OBS) was chosen as the reference period. As future climate data, RCP2.6- and RCP8.5-scenarios were available, each with three warming stages represented by minimum, mean and maximum temperature increase (-MIN, -MED, and -MAX respectively). The three-decade period 2031/2060 was selected as the comparison period for the entire study. For all maps included in this paper, decadal results are shown in addition to the three-decade graphs supporting a more detailed interpretation and showing the temporal variability. For the observational period the graphs represent the temporal development of calculated phenology and frost events, but for the scenario period they mainly illustrate the variation within the three-decadal periods.

## 2.2 Model for grapevine phenology

Grapevine phenology is described using the BBCH-scale (LORENZ et al., 1994) based on the decimal code introduced by ZADOKS et al. (1974). The main phases and their lower and upper limits are listed in Table 1. The grapevine phenology in our study was calculated using a simulation model for *Vitis vinifera* L. cv Riesling (HOPPMANN and BERKELMANN-LÖHNERTZ, 2000; STOCK et al., 2007). Previous model applications were limited to single viticultural sites (STOCK et al., 2007; HOPPMANN, 2009; HOPPMANN, 2010; KARTSCHALL et al., 2012) and to one important German viticultural area, the Rheingau region (KARTSCHALL et al., 2009). For the first time and within this study the model has been applied to cover Germany as a whole. All consecutive phases given in Table 1 were calculated by the model, but the interpretation of results focused on *bud burst* (BB) and *harvest ripeness* (HR). Daily meteorological conditions during the different phases can be used to indicate important viticultural events, e.g. frost events ( $T_{\min} < 0.0^\circ\text{C}$ ) after BB and before anthesis (*spring frost*: SF), frost during anthesis, and others. We chose to study especially the risk of SF events. SF can cause damage to the grapevine in the vegetative phase and hence result in diminished quantity and quality of harvested grapes. Furthermore, when we calculated the risk of frosts at flowering, we found only very rare occurrences for Germany in the future scenarios. Therefore we did not include this particular risk in the detailed study.

**Table 1:** Main phases of grapevine phenology on the BBCH-scale.

No.	Phase	BBCH code [Begin...End)	Calculated stage	BBCH code
1	Bud development	[00...09)	Bud burst	09
2	Vegetative development	[09...61)		
3	Flowering	[61...69)	Beginning of Flowering End of Flowering	61 69
4	Development of fruits	[69...81)		
5	Ripening	[81...89)	Beginning of Ripening	81
6	Senescence	[89...99)	Harvest Ripeness	89

### 2.2.1 Definition of spring frost risk

To quantify the risk of SF events we defined the spring frost risk ( $R_{SF}$ ) for a given time period as follows:

$$R_{SF} := \frac{n_{SF}}{n_P} \quad 0.0 \leq R_{SF} \leq 1.0 \quad (2.1)$$

with  $n_{SF}$  number of years with SF events;  
 $n_P$  period length,

which means  $R_{SF} = 0.0$  no spring frost events (spring frost free);  
 $R_{SF} = 1.0$  yearly spring frost events during the entire period.

This definition normalizes the daily indicated SF events for a whole year, and makes systematic comparison and presentation in the maps easier to handle.

### 2.2.2 Definition of potential viticultural areas

Potential viticultural areas (PVA) were defined as regions in which for all consecutive years during a given period the calculated phenology reached the phase of HR. In the scenarios, BB occurs practically for the whole of Germany, including even more elevated parts of the central German uplands, where cultivating grapevine is unrealistic because HR would rarely be reached. This led us to exclude these areas from further analysis of SF, using PVA as a filter. This reduces the calculations to reflect more realistic conditions than the simple unfiltered calculation of SF risks after BB. The high values for these areas (“no PVA”) would otherwise dominate the behaviour and maps of  $R_{SF}$ , causing unnecessary scaling and interpretation difficulties.

### 2.2.3 Declaration of decadal and three-decadal values

As symbols for the decadal averages in the observational period, and the medians and averages in the scenario periods we chose:

- BB<sub>10</sub> for BB;
- HR<sub>10</sub> for HR;
- $R_{SF10}$  for  $R_{SF}$ ;

and analogously for the three-decadal values

- BB<sub>30</sub> for BB;
- HR<sub>30</sub> for HR;
- $R_{SF30}$  for  $R_{SF}$ .

## 3 Results

### 3.1 Comparison of station- vs. grid cell-based calculations

To verify the reliability of substituting station-based calculations by calculations based on interpolated high resolution grid cell data, we compared station-based and grid-based calculated results for the 17 reference sites. Beside the station data (Table 2) we verified the four surrounding interpolation grid cells. The best fit was always found for the grid cell with an elevation closest to that of the station. Comparisons were carried out for BB, HR and  $R_{SF}$  including the time periods 1931/1960 and 1981/2010 (Table 3). Except for one site in BB<sub>30</sub> and for two sites in HR<sub>30</sub>, all differences between station-based and grid-based results were smaller than 2 days. The  $R_{SF30}$  was in accordance within an interval of  $\pm 0.1$ . Altogether we found an acceptable accordance of the results from station-based and grid-based data. The largest differences between the results appeared in cases of the largest differences in altitude between the station and the best-fit grid cell.

### 3.2 Comparison of the RCP8.5-scenario to the reference period

In our study the simulated results in the RCP2.6-scenario for BB<sub>30</sub> (Fig. 5), HR<sub>30</sub> (Fig. 6), and  $R_{SF30}$  (Fig. 7) showed only small changes compared to the observational period 1981 to 2010 (Fig. 2, Fig. 3, and Fig. 4 respectively), therefore we did not include these results in the detailed investigation presented here. We chose to use the RCP8.5-scenario bundle, selecting three paths with mainly similar behaviour (differing only in the temporal sequence of the changes, each in the order of a decade), with RCP8.5-MAX showing the fastest changes, followed a decade later by RCP8.5-MED and another decade later by RCP8.5-MIN. This synchronized behaviour led us to focus on the MED path with the assumption the discussed results will occur in an assumed “RCP8.5-future” with a rough uncertainty of almost one decade.

**Table 2:** Station-based calculated values of phenology and spring frost risk during the observational periods 1931/1960 and 1981/2010, and the scenario period 2031/2060 for the German quality wine regions.

No.	Wine region	Station	Calculated values (station-based)											
			1931/1960			1981/2010			RCP2.6MED 2031/2060			RCP8.5MED 2031/2060		
			BB [DOY]	HR [DOY]	SF risk [NUMBER]	BB [DOY]	HR [DOY]	SF risk [NUMBER]	BB [DOY]	HR [DOY]	SF risk [NUMBER]	BB [DOY]	HR [DOY]	SF risk [NUMBER]
1	Ahr	Bad Neuenahr-Ahrw.	117.7	289.6	0.37	115.2	284.7	0.10	116.5	282.0	0.32	106.0	271.0	0.36
2.1	Baden	Freiburg i.Br.	111.5	281.3	0.10	107.1	276.9	0.10	109.0	276.0	0.13	91.0	265.0	0.07
2.2	Baden	Eichstetten	110.8	280.0	0.17	106.5	276.3	0.10	107.0	274.5	0.13	91.0	265.0	0.10
3	Franken	Würzburg	122.1	295.6	0.23	118.9	289.0	0.10	120.0	287.0	0.19	109.5	273.0	0.38
4	Hessische Bergstr.	Heidelberg	116.8	285.5	0.07	111.0	280.0	0.10	114.0	278.0	0.06	100.0	268.0	0.12
5	Mittelrhein	Koblenz	116.6	283.3	0.23	112.4	277.6	0.20	114.0	275.0	0.29	98.0	265.0	0.30
6	Mosel	Bernkastel-Kues	116.8	284.1	0.23	114.9	281.4	0.10	116.0	278.0	0.20	103.0	268.0	0.26
7	Nahe	Roxheim	120.0	288.9	0.43	117.1	282.4	0.10	118.0	279.0	0.30	108.0	269.5	0.47
8	Pfalz	Bad Bergzabern	119.0	292.8	0.23	115.7	288.2	0.03	117.0	286.0	0.17	104.0	275.0	0.30
9	Rheingau	Geisenheim	119.3	289.8	0.23	116.2	284.2	0.03	117.0	281.0	0.17	106.0	271.0	0.19
10	Rheinhausen	Alzey	121.7	294.5	0.47	117.9	287.6	0.03	119.0	285.0	0.23	108.0	273.0	0.39
11.1	Saale-Unstrut	Artern	124.5	294.2	0.20	120.8	noPVA	noPVA	122.0	288.0	0.24	112.0	276.0	0.36
11.2	Saale-Unstrut	Bad Bibra	122.8	289.9	0.23	118.8	286.1	0.10	120.0	285.0	0.20	108.5	272.0	0.42
12.1	Sachsen	Dresden	127.1	296.9	0.13	123.1	noPVA	noPVA	123.0	292.0	0.13	115.0	279.5	0.18
12.2	Sachsen	Coswig	124.3	291.7	0.10	119.7	288.9	0.07	121.0	287.0	0.08	111.0	275.5	0.19
13.1	Württemberg	Öhringen	121.5	294.1	0.30	117.5	285.9	0.13	118.0	285.0	0.24	107.0	272.0	0.39
13.2	Württemberg	Obersulm-Willsbach	120.2	291.1	0.33	116.2	283.6	0.17	117.0	282.0	0.18	104.0	270.0	0.42
	All Regions	Mean value	119.6	289.6	0.24	115.8	283.5	0.10	117.0	282.4	0.19	104.8	271.1	0.29
		St. Dev.	4.3	5.1	0.11	4.5	4.3	0.05	4.2	5.1	0.07	6.7	4.1	0.13
		Minimum	110.8	280.0	0.07	106.5	276.3	0.03	107.0	274.5	0.06	91.0	265.0	0.07
		Maximum	127.1	296.9	0.47	123.1	289.0	0.20	123.0	292.0	0.32	115.0	279.5	0.47

DOY = Day of Year

noPVA = not a potential viticultural area

**Table 3:** Deviations between grid-based and station-based calculation of phenology and spring frost risk during the observational periods 1931/1960 and 1981/2010 for the German quality wine regions.

No.	Wine region	Station	Difference grid-based and station-based results					
			1931/1960			1981/2010		
			BB [DOY]	HR [DOY]	SF risk [NUMBER]	BB [DOY]	HR [DOY]	SF risk [NUMBER]
1	Ahr	Bad Neuenahr-Ahrweiler	2.8	7.2	0.03	3.5	5.3	0.03
2.1	Baden	Freiburg i.Br.	-1.1	-0.9	0.07	-1.9	-1.2	0.00
2.2	Baden	Eichstetten	0.0	0.0	0.00	0.0	-0.1	0.00
3	Franken	Würzburg	0.5	0.9	0.04	0.5	0.9	0.00
4	Hessische Bergstr.	Heidelberg	0.0	0.0	0.00	0.0	0.0	0.00
5	Mittelrhein	Koblenz	-0.3	-0.8	-0.06	-0.8	-0.8	0.03
6	Mosel	Bernkastel-Kues	-0.5	-1.0	0.00	-1.8	-0.8	0.03
7	Nahe	Roxheim	0.0	0.0	0.00	0.0	0.0	0.00
8	Pfalz	Bad Bergzabern	-0.3	-0.6	0.00	-0.5	-0.8	0.04
9	Rheingau	Geisenheim	-0.8	-1.9	-0.03	-1.0	-1.0	0.04
10	Rheinhausen	Alzey	1.2	3.5	-0.10	1.2	2.3	0.00
11.1	Saale-Unstrut	Artern	-0.4	-1.0	0.03	-0.5	noPVA	noPVA
11.2	Saale-Unstrut	Bad Bibra	0.0	0.0	0.00	0.0	0.0	0.00
12.1	Sachsen	Dresden	0.4	1.4	0.00	0.4	noPVA	noPVA
12.2	Sachsen	Coswig	0.0	0.0	0.00	0.0	0.0	0.00
13.1	Württemberg	Öhringen	-0.9	-1.6	0.00	-0.9	-1.6	0.00
13.2	Württemberg	Obersulm-Willsbach	0.5	1.0	-0.03	0.4	0.8	-0.04
	All Regions	Mean value	0.1	0.4	0.00	-0.1	0.2	0.01
		St. Dev.	0.9	2.2	0.04	1.2	1.7	0.02
		Minimum	-1.1	-1.9	-0.10	-1.9	-1.6	-0.04
		Maximum	2.8	7.2	0.07	3.5	5.3	0.04

DOY = Day of Year

noPVA = not a potential viticultural area

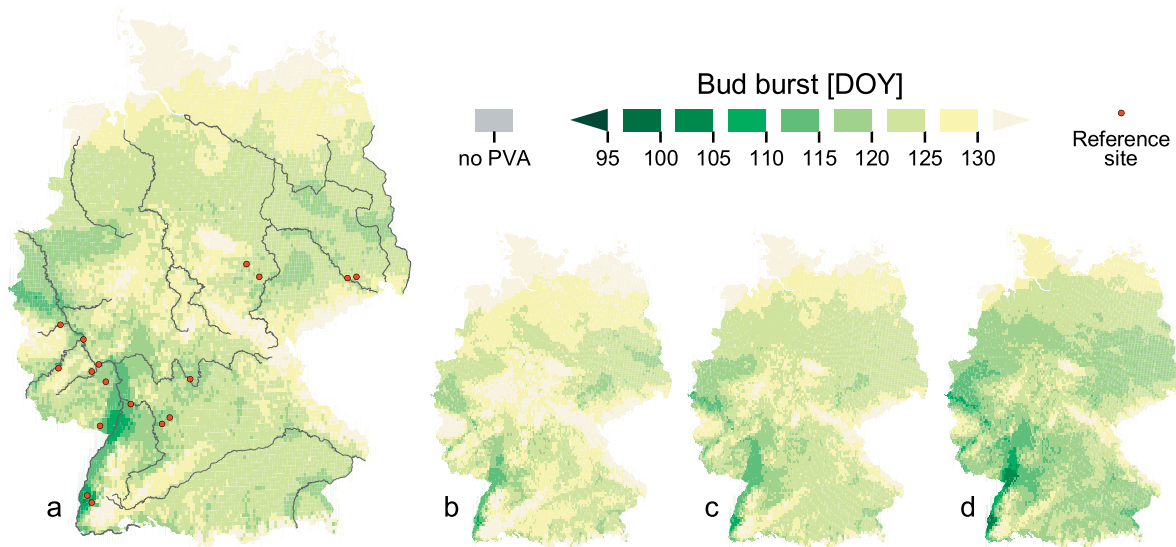
### 3.3 Development of bud burst

Comparing the selected stations during the reference period, a wide variation of bud burst was calculated. It ranged from mid-April for the growing region of Baden in southern Germany to the end of April for the more eastern and northern Franken, Saale-Unstrut and Sachsen regions (Table 2) with an average of BB<sub>30</sub> on April 26<sup>th</sup> ± 5 d. Compared with an earlier three-decade period 1931/1960 (BB<sub>30</sub> on April 30<sup>th</sup> ± 4 d), this period showed a moderately earlier BB<sub>30</sub> (-4 d ± 1 d) in the station-based results (Table 4). In the separate decades we found a rapid acceleration of bud burst (Fig. 2a–d),

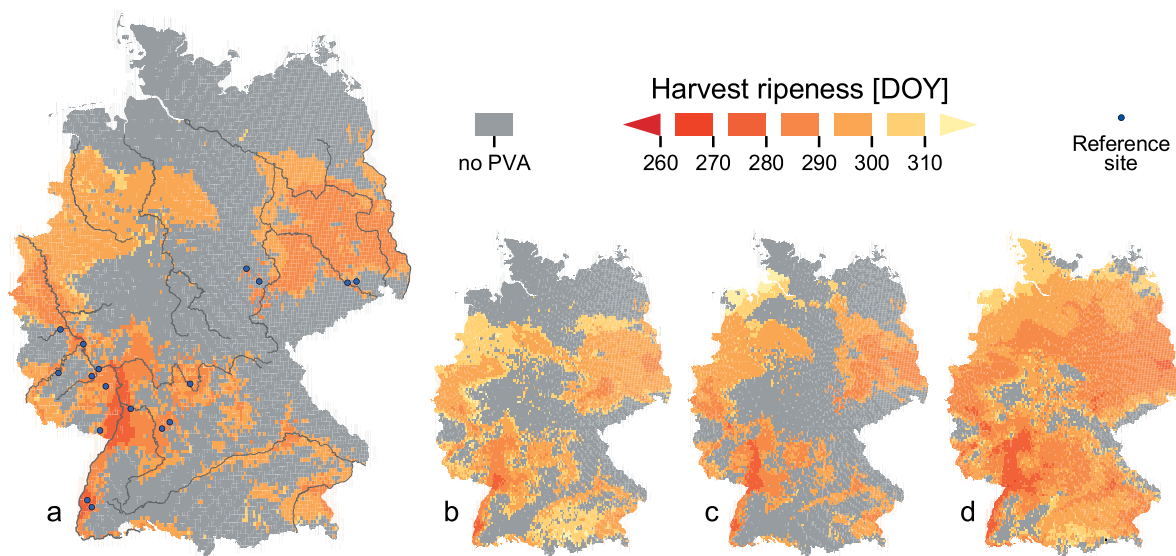
especially during the last OBS decade, bringing BB<sub>10</sub> to April 23<sup>rd</sup> ± 6 d.

In the grid-based results a very early BB<sub>10</sub> on April 10<sup>th</sup> appeared for the first time within 23 grid cells in the simulations, located around Freiburg and Eichstetten, as the earliest decadal average for bud burst. In good accordance, April 13<sup>th</sup> was found for Eichstetten as the earliest BB<sub>10</sub> for all station-based results during this decade.

In general, the acceleration continued for the RCP8.5-scenario (Fig. 8, Table 2). All traditional viticulture areas show this acceleration along all three



**Figure 2:** Average of bud burst (DOY = day of year) during the reference period, (a) three-decade 1981/2010, (b) decade 1981/1990, (c) decade 1991/2000, and (d) decade 2001/2010.



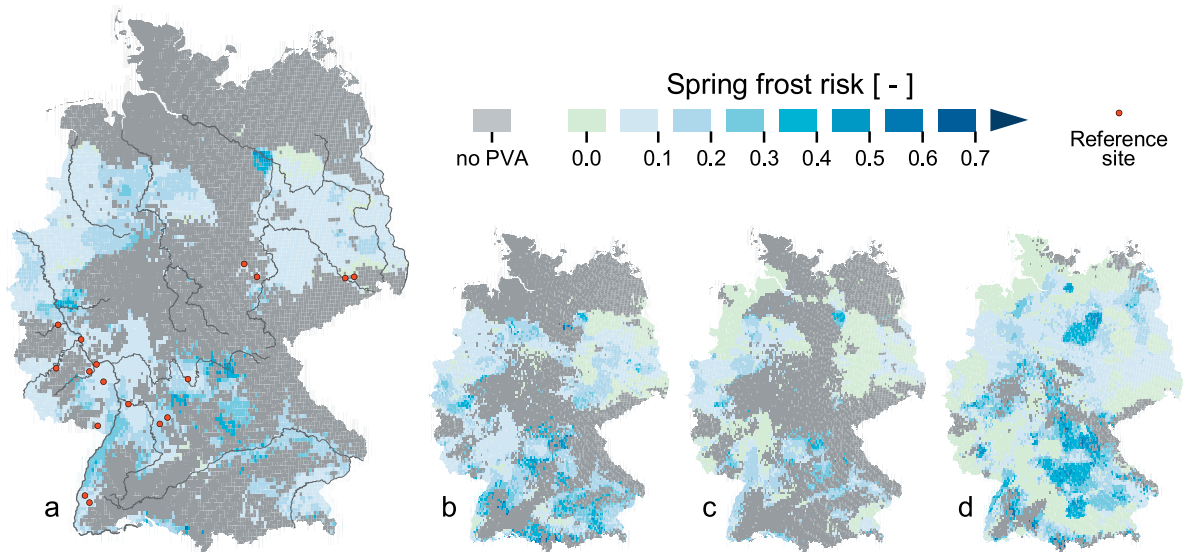
**Figure 3:** Average of harvest ripeness (DOY = day of year) during the reference period, (a) three-decade 1981/2010, (b) decade 1981/1990, (c) decade 1991/2000, and (d) decade 2001/2010.

warming paths of the RCP8.5-scenario too, bringing the station-average of  $BB_{30}$  to April 15<sup>th</sup>. The regions that showed the earliest BB during OBS revealed the strongest acceleration for the scenario period, too (Table 4), with  $BB_{30}$  at April 1<sup>st</sup> for Baden and at April 8<sup>th</sup> for Mittelrhein. The latest bud burst still appeared with  $BB_{30}$  between April 19<sup>th</sup> and 25<sup>th</sup> for Sachsen, Saale-Unstrut and Franken. The rough sequence of wine regions will stay stable in the future, probably with increasing differences.

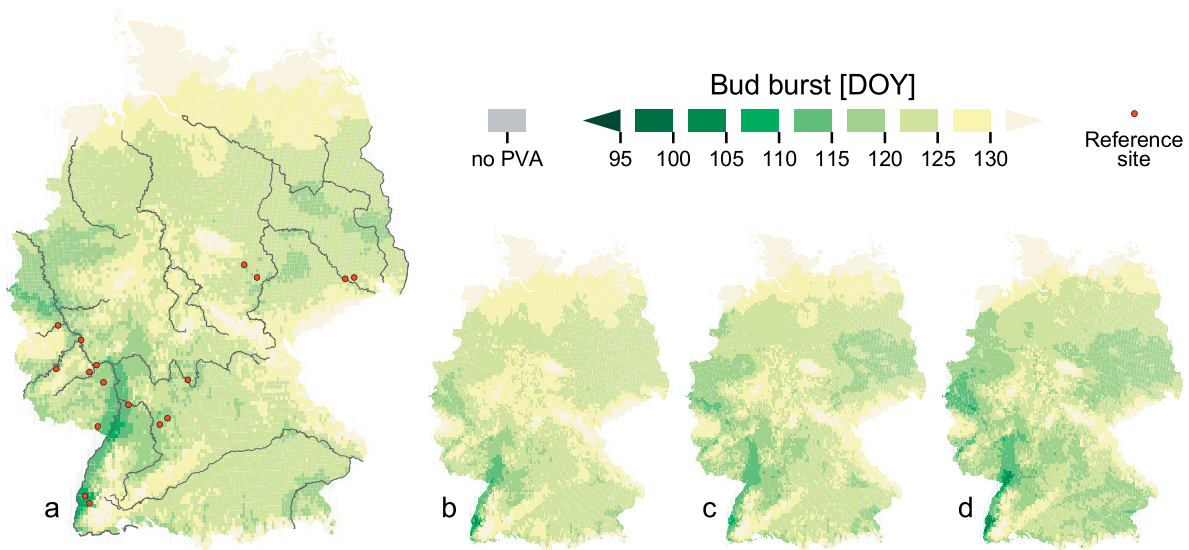
The earlier bud burst appeared in the grid-based results too, identified by reaching  $BB_{30}$  on or before April 10<sup>th</sup> within 300 grid cells, now not only around Freiburg and Eichstetten, but covering practically the complete Upper Rhine Valley.

### 3.4 Harvest ripeness and potential viticultural areas

During the three-decade OBS period (Fig. 3) a significant increase in PVA appeared. This coverage visibly



**Figure 4:** Average of spring frost risk during the reference period, (a) three-decade 1981/2010, (b) decade 1981/1990, (c) decade 1991/2000, and (d) decade 2001/2010.



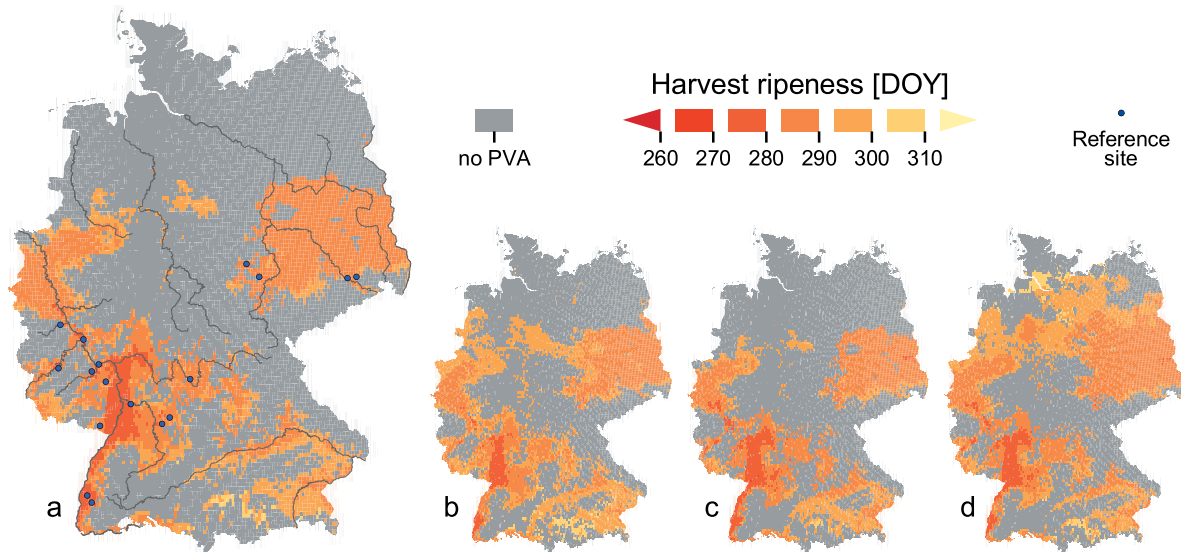
**Figure 5:** Median of bud burst (DOY = day of year) during the scenario period for RCP2.6-MED, (a) three-decade 2031/2060, (b) decade 2031/2040, (c) decade 2041/2050, and (d) decade 2051/2060.

grew from 38 % (1981/1990) up to 83 % (2001/2010) or from 6299 to 13907 grid cells (cp. Fig. 3b–d). Obviously this corresponds with the earliness in harvest ripeness.

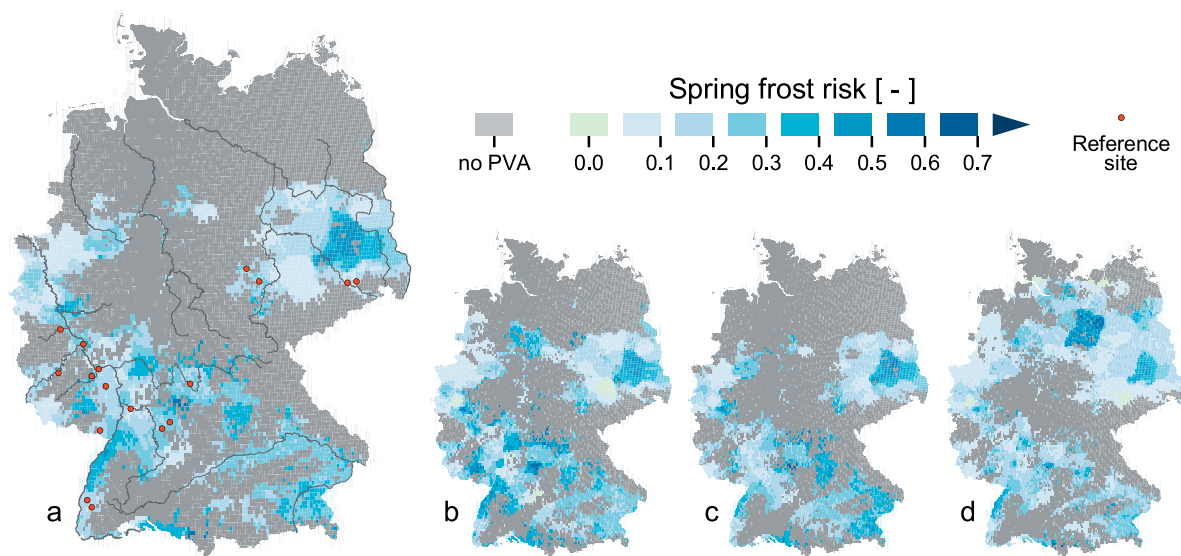
For the sake of completeness we mention here the results for the RCP2.6-scenario. In the moderate RCP2.6-scenario the isolated parts of PVA (coverage 31 % or 5213 grid cells) stayed more or less unchanged with some fluctuations (cp. Fig. 6). Since the changes in this scenario were comparatively small and the behaviour

was similar to the OBS, we did not include this scenario in the detailed investigation, as already mentioned in section 3.2.

A rapidly and continuously growing part of Germany is designated as PVA in all three RCP8.5 branches. The 2031/2040 decade (Fig. 9b) shows almost all of Germany as a large connected PVA for RCP8.5-MED (HR<sub>30</sub> coverage of 83 % or 13907 cells), except the most northern parts and mountain areas. For both the RCP8.5-MED and -MIN paths this development (HR<sub>30</sub> coverage



**Figure 6:** Median of harvest ripeness (DOY = day of year) during the scenario period for RCP2.6-MED, (a) three-decade 2031/2060, (b) decade 2031/2040, (c) decade 2041/2050, and (d) decade 2051/2060.



**Figure 7:** Average of spring frost risk during the scenario period for RCP2.6-MED, (a) three-decade 2031/2060, (b) decade 2031/2040, (c) decade 2041/2050, and (d) decade 2051/2060.

of 68 % or 11376 cells) needs one or two decades longer than for the MAX path (HR<sub>30</sub> coverage of 91 %; 15302 cells), but all paths reach quasi-saturation during the period 2031/2060. For this rough estimate, the figures given for  $R_{SF10}$  can easily be used, taking into account just the area coverage as indicator for reaching HR during the entire period.

Even the station-average HR<sub>30</sub> developed from October 11<sup>th</sup> (OBS) to September 28<sup>th</sup> for the scenario period, thereby gaining 2 days more than BB<sub>30</sub>, the dif-

ferences between the stations were smaller than for bud burst (Table 4).

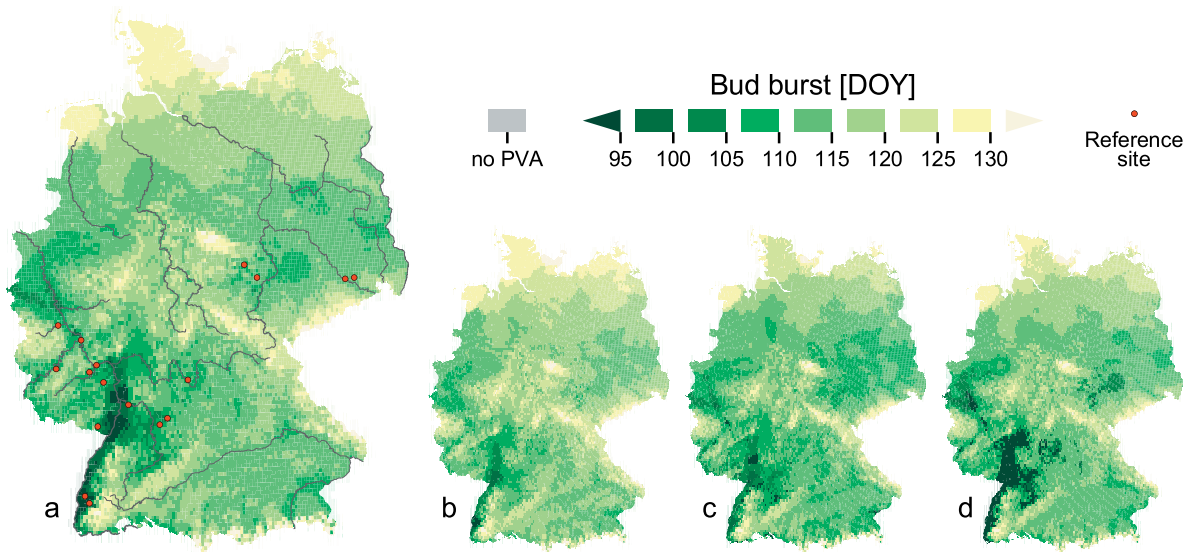
If other conditions necessary to achieve successful and sustainable viticulture are neglected, these results could draw an over-optimistic picture of the future potential of viticulture in Germany. There is already an ongoing expansion of viticulture (although up to now not as quality wine regions) in eastern and northern Germany. We will examine this development especially in section 3.5, looking at  $R_{SF}$ .

**Table 4:** Differences in station-based calculated phenology and spring frost risk between the reference (1981/2010) and RCP8.5-MED scenario period (2031/2060) for the German quality wine regions.

No.	Wine region	Station	Difference between time periods – stations								
			OBS			RCP2.6MED			RCP8.5MED		
			1981/2010–1931/1960	2031/2060–1981/2010	2031/2060–1981/2010	BB	HR	SF risk	BB	HR	SF risk
			BB	HR	SF risk	BB	HR	SF risk	BB	HR	SF risk
			[DOY]	[DOY]	[NUMBER]	[DOY]	[DOY]	[NUMBER]	[DOY]	[DOY]	[NUMBER]
1	Ahr	Bad Neuenahr-Ahrw.	-2.5	-4.9	-0.27	1.3	-2.7	0.22	-9.2	-13.7	0.26
2.1	Baden	Freiburg i.Br.	-4.3	-4.5	0.00	1.9	-0.9	0.03	-16.1	-11.9	-0.03
2.2	Baden	Eichstetten	-4.2	-3.8	-0.07	0.5	-1.8	0.03	-15.5	-11.3	0.00
3	Franken	Würzburg	-3.2	-6.6	-0.13	1.1	-2.0	0.09	-9.4	-16.0	0.28
4	Hessische Bergstr.	Heidelberg	-5.8	-5.5	0.03	3.0	-2.0	-0.04	-11.0	-12.0	0.02
5	Mittelrhein	Koblenz	-4.2	-5.7	-0.03	1.6	-2.6	0.09	-14.4	-12.6	0.10
6	Mosel	Bernkastel-Kues	-1.9	-2.8	-0.13	1.1	-3.4	0.10	-11.9	-13.4	0.16
7	Nahe	Roxheim	-2.8	-6.5	-0.33	0.9	-3.4	0.20	-9.1	-12.9	0.37
8	Pfalz	Bad Bergzabern	-3.3	-4.6	-0.20	1.3	-2.2	0.14	-11.7	-13.2	0.27
9	Rheingau	Geisenheim	-3.1	-5.5	-0.20	0.8	-3.2	0.14	-10.2	-13.2	0.16
10	Rheinhessen	Alzey	-3.8	-6.8	-0.44	1.1	-2.6	0.20	-9.9	-14.6	0.36
11.1	Saale-Unstrut	Artern	-3.7	noPVA	noPVA	1.2	noPVA	noPVA	-8.8	noPVA	noPVA
11.2	Saale-Unstrut	Bad Bibra	-4.0	-3.8	-0.13	1.2	-1.1	0.10	-10.3	-14.1	0.32
12.1	Sachsen	Dresden	-4.0	noPVA	noPVA	-0.1	noPVA	noPVA	-8.1	noPVA	noPVA
12.2	Sachsen	Coswig	-4.6	-2.8	-0.03	1.3	-1.9	0.01	-8.7	-13.4	0.12
13.1	Württemberg	Öhringen	-4.0	-8.2	-0.17	0.5	-0.9	0.11	-10.5	-13.9	0.26
13.2	Württemberg	Obersulm-Willsbach	-4.0	-7.5	-0.16	0.8	-1.6	0.01	-12.2	-13.6	0.25
	All Regions	Mean value	-3.7	-5.3	-0.15	1.1	-2.1	0.10	-11.0	-13.3	0.19
		St. Dev.	0.9	1.6	0.13	0.7	0.9	0.07	2.4	1.2	0.13
		Minimum	-5.8	-8.2	-0.44	-0.1	-3.4	-0.04	-16.1	-16.0	-0.03
		Maximum	-1.9	-2.8	0.03	3.0	-0.9	0.22	-8.1	-11.3	0.37

DOY = Day of Year

noPVA = not a potential viticultural area



**Figure 8:** Median of bud burst (DOY = day of year) during the scenario period for RCP8.5-MED, (a) three-decade 2031/2060, (b) decade 2031/2040, (c) decade 2041/2050, and (d) decade 2051/2060.

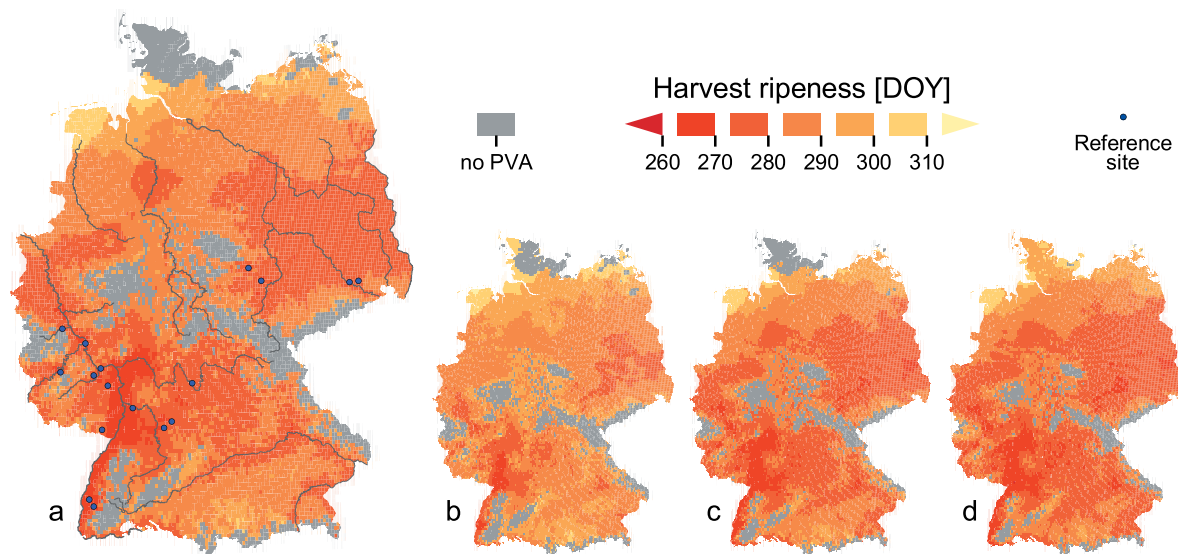
### 3.5 Spring frost risk

If one looks at spring frost events rather than the purely phenological behaviour, the picture differs. During OBS the risk of spring frost events within the traditional areas decreased, but did not disappear completely (Table 2). The overall increase of  $R_{SF10}$  in Fig. 4d for the last decade 2001/2010 did not affect the German quality wine regions, occurring mainly within the new PVAs.

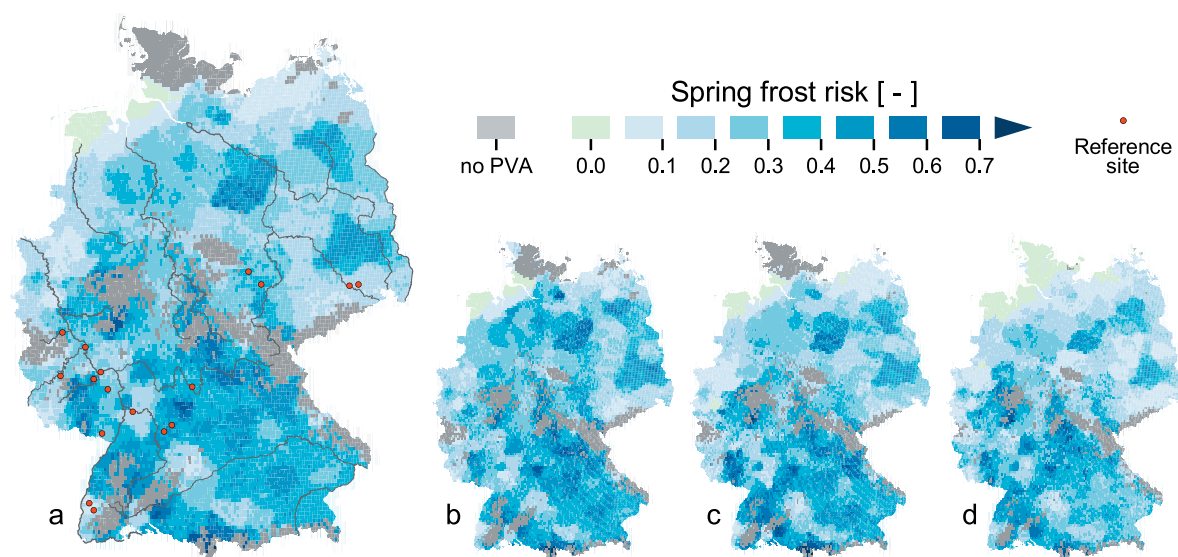
For the future this picture will become more complex. We were able to condense two essential findings:

1. Under further warming, the risk of spring frost events at least will not decrease. We found a general increase in this risk all over Germany (Fig. 10). A decreasing risk was calculated only for some small regions, for example in the south-west of Germany. Here the station-based results showed two stations in the Baden vine growing region indicating stagnation





**Figure 9:** Median of harvest ripeness (DOY = day of year) during the scenario period for RCP8.5-MED, (a) three-decade 2031/2060, (b) decade 2031/2040, (c) decade 2041/2050, and (d) decade 2051/2060.



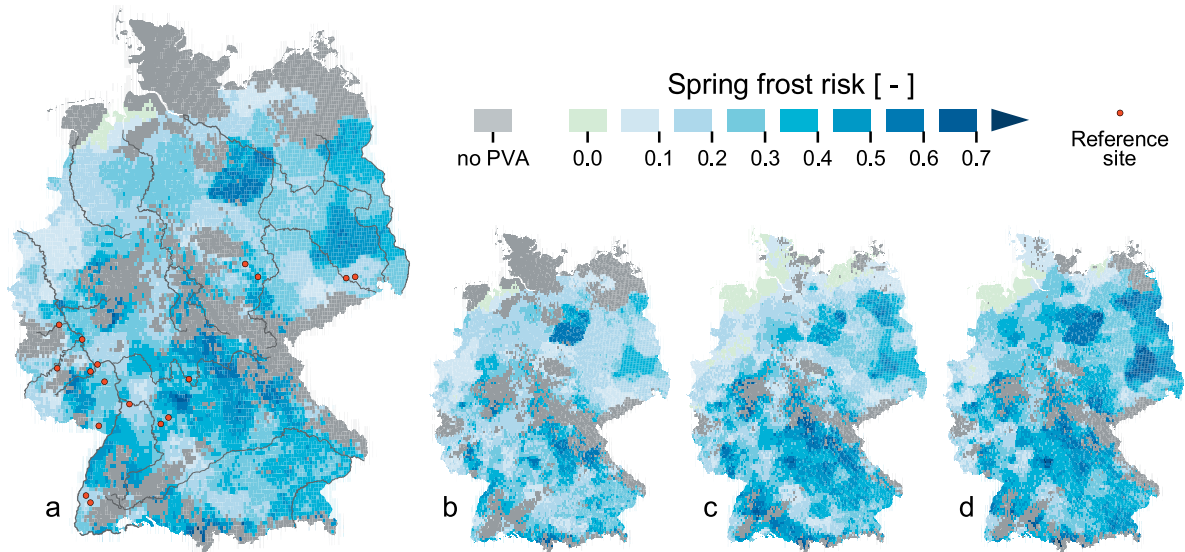
**Figure 10:** Average of spring frost risk during the scenario period for RCP8.5-MED, (a) three-decade 2031/2060, (b) decade 2031/2040, (c) decade 2041/2050, and (d) decade 2051/2060.

with  $\Delta R_{SF} = 0.00$  for Eichstetten, or a very slight decrease with  $\Delta R_{SF} = -0.03$  for Freiburg (cp. Table 2, Table 4). Nevertheless the dominant tendency of increasing  $R_{SF}$  appeared both in the grid-based and the station-based results.

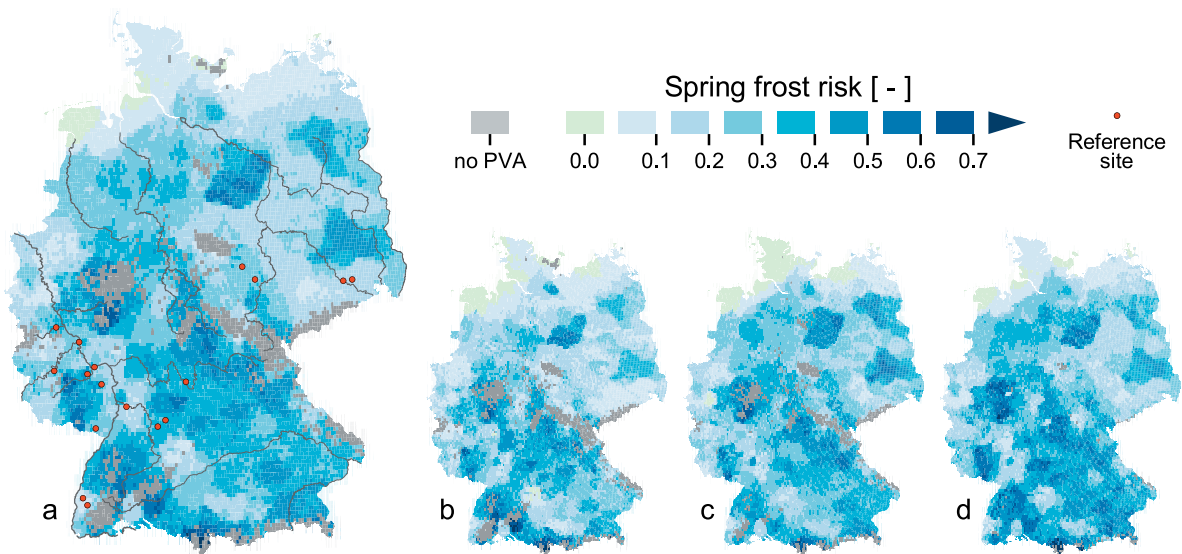
- For all three future warming paths included in the RCP8.5-scenario we found similar behaviour of SF risk not showing a distinct delay between the different warming paths (Fig. 10-12). This indicates a kind

of equilibrium between a slightly decreasing meteorological frost risk due to rising temperatures and a shift to earlier BB into periods with persistent frost events.

These findings lead us to some remarks on the further development of viticulture in Germany. In general, the earlier BBs will be not paralleled by a decreasing risk of spring frost events. The trend of expanding viticulture beyond the traditional regions is connected – at least for the next decades – with the risk of spring frost events,



**Figure 11:** Average of spring frost risk during the scenario period for RCP8.5-MIN, (a) three-decade 2031/2060, (b) decade 2031/2040, (c) decade 2041/2050, and (d) decade 2051/2060.



**Figure 12:** Average of spring frost risk during the scenario period for RCP8.5-MAX, (a) three-decade 2031/2060, (b) decade 2031/2040, (c) decade 2041/2050, and (d) decade 2051/2060.

making the economic use of grapevine questionable, except in favourable frost-protected sites. For northern and eastern Germany the more frequent frost events are the result of earlier bud burst together with the stronger continental influence, but for the regions in south and western Germany, the cause is mainly the even earlier bud burst.

## 4 Discussion

Climate change-induced changes of spring frost risk develop as a result of two independent processes, the earliness of bud burst and the timing of the last frost events in spring. An estimation of climate change influences

on spring frost events proves difficult, especially at sites where grapevine is cultivated near its climate margins.

Even though a number of models for grapevine phenology already exist, model-based studies of spring frost risk remain rare. CAFFARRA and ECCEL (2011) investigated the climate impact on phenology of *Vitis vinifera* (cv. Chardonnay) in the Trentino region, and based on this model CAFFARRA et al. (2012) conducted a study of spring frost risk for cv. Müller-Thurgau in Luxembourg. Using the same model and in more detail, MOLITOR et al. (2014) investigated the frost risk after BB for this region, which can be seen as a possible reference to nearby German grapevine growing areas. They found a decreasing tendency in spring frost risk for Müller-Thurgau, mainly because their results showed less earliness in bud burst than in last spring frost. Beside the different variety (even though it is a closely related one) and different region, there are distinct differences in the used data base (i), the used phenology models (ii), and the method of result analysis (iii). These main differences are in detail:

1. Both the Luxembourg studies were based on a multi-model ensemble of the weaker warming scenario A1B (CARTER et al. 2001) compared to our clearly faster and stronger warming scenario RCP8.5.
2. CAFFARRA et al. (2012) and MOLITOR et al. (2014) took into account the influence of day length (or photoperiod) on dormancy and bud burst forcing, while we calculated BB only by summing up an asymptotic saturation function of  $T_{\max}$  and using a nonlinear heat sum built from  $T_{\max}$  and  $T_{\min}$ .
3. Following our definition (Eq. (2.1)) for  $R_{SF}$ , we counted and weighted years with spring frost events within the investigated time periods, while CAFFARRA et al. (2012) and MOLITOR et al. (2014) analysed the probability of an overlap between the last frost event in spring and bud burst. Their method seems to be more general, hence our algorithm directly calculates a measure for spring frost risk.

Therefore a simple comparison of the different tendencies for the risk development does not seem feasible. Nevertheless, according to the results presented here, the Luxembourg studies indicate that spring frost events at least will not disappear in the coming decades. A direct comparison of simulation results originating from different models requires studies conducted on the same data base and with the same methodology for the result analysis.

## 5 Conclusions

Especially during the last three decades, German viticulture has rather profited from the already ongoing global warming (earlier bud burst together with a decreasing spring frost risk, higher total soluble solids, earlier fruit

ripening due to the longer vegetation period). Model results show that in future this acceleration of phenology will continue. Beyond that, we found strong indications for some problems under continuous warming. The decrease in risk of spring frost events will not only be interrupted, but the number of such events will very probably increase in future, even after an intermediate period of a lower level during the last decades. This increase will affect southern and western wine regions too, which have hitherto benefitted from global warming phenomena.

The calculated climate impact on ripening in our study is composed of the acceleration effect on phenology and a comparable moderate warming between September and October. A main effect is that ripening is shifted to an earlier and significantly warmer time (August instead of September) within the vegetation period. This will have significant consequences: grapevine will ripen under clearly different conditions (especially higher night-time temperatures) which may influence the composition of flavours in grapes at vintage and the typical character of the German quality wines.

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