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VITICULTURE ORIGINAL RESEARCH ARTICLES

UniPhen "PIWI"—high-resolution simulation of the phenological development of 13 fungus-tolerant cultivars based on a broad observation data set from Central Europe

Daniel Molitor[1,*], Kristina Heilemann[1], César Dionisio Jiménez-Rodríguez[1], Silke Hüther[2], Oliver Trapp[2], Anouck Stalport[3], Julien Louvieaux[3,4], Olivier Viret[5], Martin Ladach[6], Stefan Schumacher[7], Bettina Lindner[8], Pierre-Henri Dubuis[9], Anne-Lise Fabre[9], Michael Weber[10], Arno Schmid[11], Josef Terleth[11], Wolfgang Renner[12], Benjamin Foerg[13], Kathleen Mackie-Haas[14], Jürgen Junk[1]

[1] Luxembourg Institute of Science and Technology (LIST), Environmental Sensing and Modelling research unit, 41, rue du Brill, L-4422 Belvaux, Luxembourg
[2] Julius Kuehn Institute, Institute for Grapevine Breeding, Geilweilerhof, D-76833 Siebeldingen, Germany
[3] Haute Ecole provincial de Hainaut Condorcet, Laboratory of Applied Plant Ecophysiology, 1, rue de l'académie, B-7810 Ath, Belgium
[4] Centre pour l'Agronomie et l'Agro-industrie de la Province de Hainaut, 11, rue Paul Pastur, B-7800 Ath, Belgium
[5] General Direction of Agriculture, Viticulture and Veterinary Affairs, 29, avenue de Marcelin, CH-1110 Morges, Switzerland
[6] Dienstleistungszentrum Ländlicher Raum (DLR) Rheinpfalz, Institute of Viticulture and Enology, Breitenweg 71, D-67435 Neustadt/Weinstraße, Germany
[7] State Institute of Viticulture and Oenology (WBI), Merzhauser Str. 119, D-79100 Freiburg, Germany
[8] Hochschule Geisenheim University, Department of Plantbreeding, Von-Lade-Str. 1, D-65366 Geisenheim, Germany
[9] Agroscope, Département fédéral de l'économie, de la formation et de la recherche DEFR 60, route de Duillier, CH-1260 Nyon, Switzerland
[10] Dienstleistungszentrum Ländlicher Raum (DLR) Mosel, Gartenstraße 18, D-54470 Bernkastel-Kues, Germany
[11] Laimburg Research Centre, Laimburg 6, I-39040 Pfatten, Italy
[12] Versuchsstation Obst- und Weinbau Haidegg, Ragnitzstraße 193, A-8047 Graz, Austria
[13] Dienstleistungszentrum Ländlicher Raum (DLR) Rheinhessen-Nahe-Hunsrück, Viticulture Group, Rüdesheimer Straße 60-68, D-55545 Bad Kreuznach, Germany
[14] Agroscope, Schlossgass 8, CH-8820 Wädenswil, Switzerland

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*correspondence: daniel.molitor@list.lu

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ABSTRACT

Due to their high potential for fungicide reduction, fungus-tolerant "PIWI" cultivars are increasingly gaining interest in European viticulture. This investigation aimed (i) to obtain phenological observation datasets of PIWI cultivars across a broad set of European locations, (ii) to apply the temperature sum based "UniPhen" model allowing for a precise simulation of the phenological development at all BCCH stages between bud swelling and berries ripe for harvest and (iii) to discuss the potential implementations in applied viticulture as well as in viticultural climate change impact research.

Four consecutive years of complete data sets of phenological observations originating from eight locations in Central Europe for 13 PIWI and 3 traditional cultivars were used to apply the UniPhen model using a cumulative degree day approach with three temperature thresholds (lower threshold: 10 °C; upper threshold: 20 °C; heat threshold: 30 °C). Muscaris showed the thermal-temporally earliest budburst, while Solaris was earliest in beginning of flowering and harvest ripeness. The latest budburst and the latest beginning of flowering in PIWI cultivars were observed in Pinotin, while harvest ripeness was reached latest by Calardis blanc. The average normalised standard deviation ($SD_{15\ °C}$) over all stages, locations and cultivars was 5.5, corresponding to 5.5 days at 15 °C, with the lowest $SD_{15\ °C}$ values around budburst and flowering stages. The highest $SD_{15\ °C}$ values were observed in the bunch closure and post-veraison stages.

UniPhen "PIWI" enables a precise simulation of all 31 BBCH stages between the beginning of the bud swell (01) and berries being ripe for harvest (89) for 13 fungus-tolerant cultivars and can be extended to additional cultivars. The model can be applied (i) as a bioclimatic indicator describing the suitability of a location/region for the cultivation of specific cultivars under present and future climate conditions, (ii) for the simulation of cultivar-specific phases of highest susceptibility for fungal diseases and, indirectly, the timing of fungicide treatments as well as (iii) for the classification of the relative late frost risk depending on the thermal-temporal precocity of budburst. This knowledge helps to lower the barrier to growing PIWI cultivars and helps to pave the way for a more sustainable, climate change-resilient viticulture.

KEYWORDS: cumulative degree days, climate change adaptation, climate change mitigation, fungus-tolerant cultivars, high resolution phenological model, PIWI, UniPhen

INTRODUCTION

Grapevine (*Vitis vinifera* L.) phenology is mainly temperature-driven (Jones, 2013). Air temperature is the main factor influencing the timing of phenological phases (*e.g.*, Gladstones, 2011; Jones, 2013) if water and radiation requirements of the plants are fulfilled (Nendel, 2010; Webb *et al.,* 2007). Consequently, grape phenology models in viticulture are usually based on air temperature observation data as a single input parameter (*e.g.*, Caffara & Eccel, 2010; Cola *et al.,* 2014; Molitor *et al.,* 2014b; Parker *et al.,* 2011; Parker *et al.,* 2020).

Many phenological models assume linear forcing effects of air temperature by accumulating temperatures above a defined threshold to temperature sums or cumulative degree days (*e.g.*, Amerine & Winkler, 1944; Duchêne *et al.,* 2010; Nendel, 2010; Parker *et al.,* 2011). However, in such unlimited temperature sum approaches the physiological evidence that above plant-specific threshold temperatures the forcing effect of the temperature will not increase further or even tends to decrease is neglected (Bonhomme, 2000; Molitor *et al.,* 2014b; Wang & Engel, 1998; Yan & Hunt, 1999). Consequently, Molitor *et al.* (2014b) incorporated (i) an upper threshold temperature and (ii) a heat threshold temperature in their temperature sum-based model approach and demonstrated a significantly improved model accuracy compared to the uncapped cumulative degree day approaches previously published. Meanwhile, this approach has been proven to be of high accuracy in a broad range of cultivars using a unified threshold triplet of 10, 20 and 30 °C as lower, upper and heat temperature thresholds (Molitor *et al.,* 2020). This "UniPhen" approach is covering all phenological stages according to the BBCH scale and is open for the incorporation of any other grape cultivar based on high-resolution observation data (Molitor *et al.,* 2020).

Climate change is threatening viticultural production (van Leeuwen *et al.,* 2024). Global near-surface mean air temperature has increased by over 1 °C over the past century, and all major climate projections are projecting a further increase by up to 3 °C by 2100 (IPCC, 2021). Moreover, global warming is expected to lead to a general increase in the frequency and intensity of extreme weather events (IPCC, 2021) such as droughts and heat waves (Fraga *et al.,* 2020), threatening grape yield as well as wine quality and typicity.

In viticulture, weather and climate control grapevine growth, physiology, yield, and berry composition (Santos *et al.,* 2020). Hence, climate change is a direct threat to the socio-economic sustainability of many viticultural regions (*e.g.*, Lereboullet *et al.,* 2013; Mosedale *et al.,* 2016). Furthermore, a large portion of the total active ingredient volume of pesticides used in agriculture is applied in vineyards, and the use of fungicides in viticulture alone accounts for more than 70 % of the total fungicide use in Europe (Wingerter *et al.,* 2021). Via the application of fungicides, viticulture contributes to climate change by releasing greenhouse gases during pesticide synthesis, transport, and application in the field via viticultural machinery. Addressing climate change in viticulture requires significant efforts to (i) adapt to changing environmental conditions as well as (ii) mitigate greenhouse gas emissions by promoting more sustainable forms of vineyard management.

In this context, the cultivation of new fungus-tolerant or fungus-resistant grape cultivars (Töpfer & Trapp, 2022), the so-called "PIWIs - pilzwiderstandsfähige Rebsorten", has received increasing attention in recent years as they bear the potential to address climate change adaptation and mitigation simultaneously. PIWIs are new, cross-bred cultivars bearing resistance genes stemming from American or Asian *Vitis* species (Pedneault & Provost, 2016) and display reduced susceptibility towards major fungal diseases in viticulture, namely downy and powdery mildew. Consequently, PIWI cultivation allows for a substantial reduction in the use of fungicides (minus 50–80 %) (Töpfer & Trapp, 2022), which represent 96 % of pesticides used in viticulture (Marinho *et al.,* 2020).

By increasing PIWI cultivation, the wine industry could thus actively contribute to reducing greenhouse gas emissions and ensure the sustainability of the sector under changing climatic conditions, while reducing its overall environmental footprint. Accordingly, increased PIWI cultivation may not only contribute to achieving pesticide reduction targets, but also to the EU Biodiversity strategy for 2030. Furthermore, the cultivation of PIWI cultivars represents an economical risk reduction strategy under increasingly frequent extreme weather conditions such as long-lasting rain periods in summer, causing severe calamites of fungal diseases and hampering access to the vineyards with machines.

Despite their potential benefits, PIWIs are presently cultivated only in 0.5 % of the viticultural area of Luxembourg (Anonymous, 2023) while in countries like Switzerland or Germany, the PIWI cultivars exceed 3 % of the nationwide planted area (Destatis, 2023; OFAG, 2023). In the relatively new and rapidly growing grape-growing country, Belgium, meanwhile, PIWIs represent 29.6 % of the viticultural area (Anonymous, 2024). Anyhow, there is still a lack of detailed information about the viticultural traits of these new cultivars, including the response of grape phenology to heat consumption that is key to consider the suitability of PIWI cultivars across different climatic conditions. The growing interest in PIWI cultivars demonstrated the need to integrate them into existing models. Hence, there is a need for more detailed and transregional studies on the differences in phenological development of different PIWI cultivars, especially in the context of climate change and fungal disease pressure.

The aim of the present investigation was (i) to obtain datasets of high-resolution phenological observations of PIWI cultivars (and traditional reference cultivars) at a broad range of European locations, (ii) to apply the temperature sum based UniPhen model for all cultivars of observation allowing for a precise simulation of the phenological development at all BCCH stages between beginning of bud swelling and berries ripe for harvest and (iii) to discuss the potential implementations of UniPhen “PIWI” in applied viticulture as well as in viticultural climate change impact research.

MATERIALS AND METHODS

1. Experimental vineyards

The phenological monitoring was carried out at 15 experimental vineyards across Europe (Figure 1). All sites are located along a topographical gradient with Ath (Belgium) and Haidegg (Austria) as the two extremes with elevations of 60 and 600 m a.s.l., respectively. All sites provide a fair representation of the climatic conditions and soil types that characterise the vineyards cultivated in Europe outside the Mediterranean region. According to the Köppen-Geiger climate distribution in Europe (Beck *et al.,* 2018), the sites Wädenswil and Haidegg characterised the continental cold climate with dry season and warm summer (Dfb), Laimburg characterised the temperate climate with hot summer and no dry season (Cfa), and the rest of the sites the temperate climate with warm summer and no dry season (Cfb). The main soil types are represented

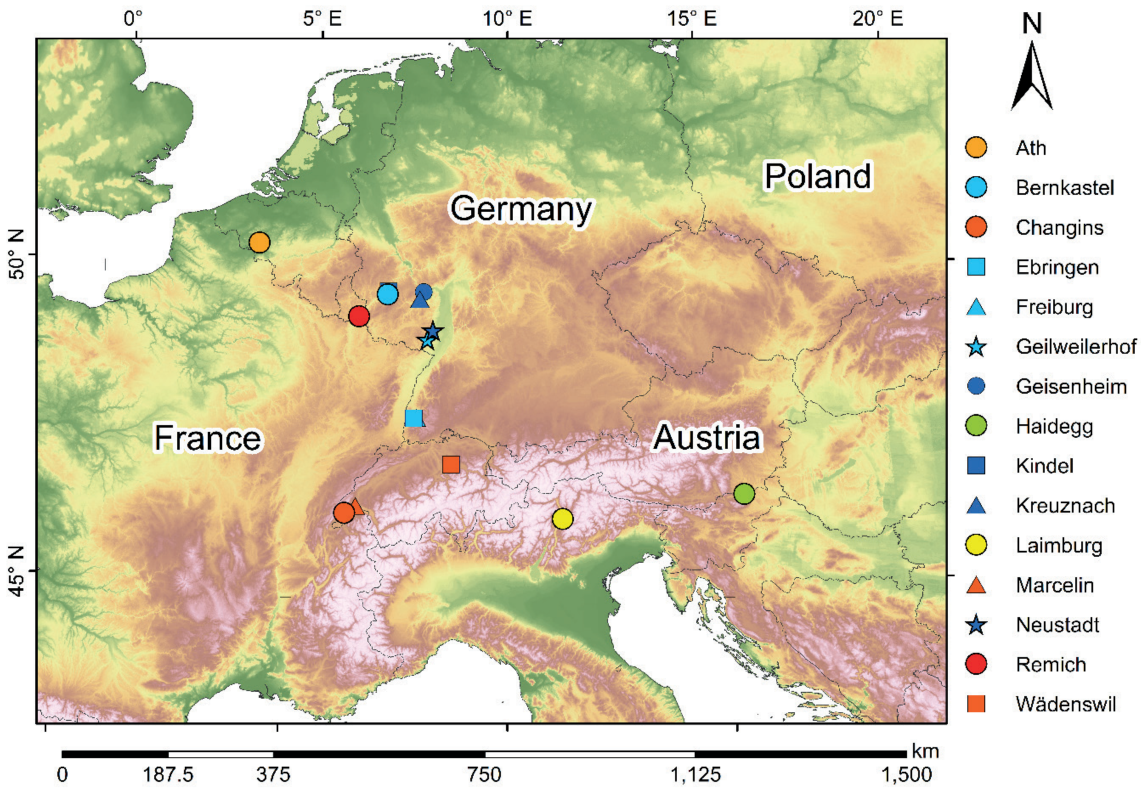

FIGURE 1. Geographical distribution of the 15 experimental vineyards across Europe. Each country is represented by an individual colour, with the exception that only Germany is represented by two shades of blue. The elevation map was retrieved from (EEA, 2016).

by a Cambisol (CM) soil unit that is present in eight of the experimental vineyards (Table 1). The Luvisol (LV) is found in Ath (Belgium) and Kreuznach (Germany), and the soil of the remaining four sites are Fluvisols (FV), Phaeozems (PH), Planosols (PL), and Regosols (RG).

Systematic phenological assessments took place in the years 2021 to 2024 in the following locations (Table 1).

Only those locations providing four years of complete data sets were selected for model calibration.

Phenology of the following cultivars was recorded: Cabernet blanc, Cabernet Cortis, Cabertin, Calardis blanc, Johanniter, Monarch, Muscaris, Pinotin, Regent, Sauvignac, Solaris, Souvignier gris, Villaris, Divico, Helios, Bronner, Cabaret noir, Cabernet Carbon, Divona, Rondo, Hibernal, Prior, Baron, Floreal, Satin noir, Vidoc, Artaban, Laurot, VB 1-22, Donauriesling, Müller-Thurgau, Pinot noir, Riesling, Chardonnay, Chasselas and Dornfelder. Only those location × cultivar combinations with complete data sets for all four years of observation, leading to at least 8 complete data sets (covering all BBCH stages between 01 and 89) per cultivar, were used as input data for model calibration (Table 2).

In total, calibration data sets consisted of the following complete data sets (covering all BBCH stages between 01 and 89 in all four years of observation) originating from the following locations (Table 3).

All cultivars were trained in a cane-pruned vertical shoot positioning system (VSP). Six plants were monitored per cultivar; the plants of observation were the same in all four years.

TABLE 1. Locations of observation, observation period, number of years with complete data sets covering all BBCH stages between 01 and 89, as well as soil types. Locations selected for model calibration are marked in bold.

Location	Country	Coordinates	Years of observation	Years with complete data sets	Soil type (EUSIS, 2023)
Remich	**Luxembourg**	**49.55 N, 06.36 E**	**2021–2024**	**4**	**Cambisol (CMvr)**
Geilweilerhof	**Germany**	**49.22 N, 08.05 E**	**2021–2024**	**4**	**Phaeozems (PHlv)**
Wädenswil	Switzerland	47.23 N, 08.68 E	2021–2023	0	–
Ath	**Belgium**	**50.62 N, 03.77 E**	**2021–2024**	**4**	**Luvisol (LVha)**
Marcelin	**Switzerland**	**46.52 N, 06.48 E**	**2021–2024**	**4**	**Cambisol (CMeu)**
Kindel	**Germany**	**49.97 N, 07.06 E**	**2021–2024**	**4**	**Cambisol (CMdy)**
Neustadt	**Germany**	**49.37 N, 08.18 E**	**2021–2024**	**4**	**Regosol (RGca)**
Freiburg	**Germany**	**47.97 N, 07.83 E**	**2021–2024**	**4**	**Cambisol (CMdy)**
Ebringen	**Germany**	**47.96 N, 07.77 E**	**2021–2024**	**4**	**Cambisol (CMca)**
Geisenheim	Germany	49.98 N, 07.93 E	2022–2024	3	Fluvisol (FLeu)
Changins	Switzerland	46.40 N, 06.23 E	2022–2023	0	Cambisol (CMeu)
Bernkastel	Germany	49.92 N, 07.04 E	2023	0	Cambisol (CMdy)
Laimburg	Italy	46.36 N, 11.28 E	2023	1	Cambisol (CMeu)
Haidegg	Austria	46.63 N, 15.50 E	2023–2024	2	Planosol (PLeu)
Kreuznach	Germany	49.86 N, 07.84 E	2023	1	Luvisol (LVha)

TABLE 2. Cultivars selected for model calibration, number of observation data set, number of complete data sets (covering all BBCH stages between 01 and 89 in all four years of observation).

Cultivar	Observation data sets	Complete data sets
Cabernet blanc	25	20
Cabernet Cortis	21	16
Cabertin	13	12
Calardis blanc	25	16
Johanniter	17	12
Monarch	12	8
Muscaris	25	16
Pinotin	14	12
Regent	19	8
Sauvignac	26	20
Solaris	30	24
Souvignier gris	24	20
Divico	18	12
Müller-Thurgau	30	24
Pinot noir	42	32
Riesling	24	20

TABLE 3. Location × cultivar combinations consisting of complete data sets (covering all BBCH stages between 01 and 89 in all four years of observation) selected for model calibration.

Location	Cabernet blanc	Cabernet Cortis	Cabertin	Calardis blanc	Johanniter	Monarch	Muscaris	Pinotin	Regent	Sauvignac	Solaris	Souvignier gris	Divico	Müller-Thurgau	Pinot noir	Riesling
Remich	X		X	X	X		X	X		X	X	X	X	X	X	X
Geilweilerhof	X	X	X	X	X	X	X	X	X	X	X			X	X	X
Ath		X			X	X	X		X		X	X		X	X	X
Marcelin													X		X	
Kindel	X									X		X		X	X	X
Neustadt	X		X	X			X	X			X				X	X
Freiburg		X		X						X	X	X	X	X	X	
Ebringen	X	X								X	X	X		X	X	

2. Assessment of phenological stages

All phenological growth stages according to the BBCH (Biologische Bundesanstalt, Bundessortenamt und Chemische Industrie) scale as defined by Lorenz *et al.* (1995) (Table S1) between BBCH 01 (beginning of bud swelling) and BBCH 85 (softening of berries) were recorded when 50 % of the vines or shoots exhibited the respective stage. The assessment intervals ranged from two to three days. Usually, records were taken at the same location by the same person in all years and cultivars. The date of BBCH 89 was defined as the DOY (day of the year) when 60° Oechsle (= 14.17 °Brix) was reached or exceeded for the first time in the respective year following the definition of Molitor *et al.* (2020). Maturity control took place at weekly intervals between veraison (BBCH 81) and harvest by collecting approximately 50 randomly selected berries (clusters from different positions of the canopy; berries from different positions in the cluster) per cultivar (avoiding berries with visible bunch rot symptoms). The date of reaching a specific phenological stage was noted as day of the year (DOY).

3. Meteorological measurements

Daily average air temperatures at 2 m height were recorded during the period of examination by standard automatic weather stations in proximity (less than 200 m) of the experimental vineyards. Average growing season (April to October) temperatures per location and year are given in Table S2.

The highest growing season temperatures were observed in the year 2022 (average 17.3 °C), which was on average 2.5 °C warmer than in 2021 (average 14.8 °C). On average, Ebringen was the location with the highest average growing season temperatures (17.5 °C), while the lowest average growing season temperatures were recorded in Ath (15.4 °C).

4. Application of the unified high-resolution phenological model approach "UniPhen"

In the present study, the approach of the high-resolution cumulative degree day-based phenological model, as previously developed for the Rivaner cultivar (Molitor *et al.,* 2014b), parameterised for Riesling (Molitor *et al.,* 2016) and Pinot noir (Molitor & Junk, 2019), as well as unified by using a unified global optimised temperature threshold triplet (lower threshold: 10 °C, heat threshold: 20 °C, heat threshold: 30 °C) (Molitor *et al.,* 2020) was applied to all selected cultivars.

In this "UniPhen" approach, degree days (DD) for a specific day are calculated based on the daily average air temperatures, applying the following conditions:

$$DD_{10,20,30} = \begin{cases} 0, & \text{if } t \leq 10\ °C \text{ or if } t \geq 40\ °C \\ (t-10), & \text{if } 10\ °C \leq t \leq 20\ °C \\ 10, & \text{if } 20\ °C \leq t \leq 30\ °C \\ 10-(t-30), & \text{if } 30\ °C \leq t \leq 40\ °C \end{cases}$$

where $DD_{10,20,30}$ is the degree day for a specific day and t is the daily average temperature.

For every growth stage, degree days (DD) were summed up to cumulative degree days (CDDs) using the Equation (1):

$$CDD_{10,20,30} = \sum_{i=m+1}^{n} DD_{10,20,30}(i) \qquad (1)$$

where $CDD_{10,20,30}$ are the cumulative degree days relative to the date of BBCH 09 in Riesling; $DD_{10,20,30}$ the value of the degree day for the day i; m the DOY when BBCH 09 was observed in Riesling; and n the DOY when the target phenological stage was reached in the respective cultivar.

The reference date was the day of the year (DOY) at which BBCH 09 was reached in Riesling (following Molitor *et al.* (2020)).

If no observation data for BBCH 09 for Riesling were available (Marcelin, Freiburg, Ebringen), its virtual DOY was calculated based on the observed DOY of BBCH 09 for Pinot noir. According to the data presented by Molitor *et al.* (2020), Pinot noir reaches BBCH 09 6.1 $CDD_{10,20,30}$ prior to Riesling. Hence, the date of BBCH 09 in Riesling was fixed at the DOY at which a temperature sum of 6.1 $CDD_{10,20,30}$ after to the DOY of observation of BBCH 09 in Pinot noir was reached or exceeded.

5. Data analysis

To determine general temperature sum thresholds to simulate all phenological stages between BBCH 01 and BBCH 89 in all cultivars, average $CDD_{10,20,30}$ were calculated for each cultivar, relative to the date of reaching BBCH 09 in Riesling. Standard deviations of the cumulative degree days were calculated for each phenological stage in each cultivar and each location. To normalise the relative value of the standard deviations caused by the daily DD values, standard deviations were divided by the theoretical DD at 15 °C (approximate growing season temperature in Remich in the period of observation, selected following Molitor *et al.* (2020)). These normalised standard deviations, $SD_{15°}$ are given for all phenological stages, all cultivars and all locations.

The R script used to calculate the CDD per cultivar is available in Jiménez-Rodríguez (2024) as UNIPHEN-Tool v1.0.0.

To assess the goodness of fit of the model, mean bias errors (MBE) and mean absolute errors (MAE) were calculated for all years, locations and cultivars as an average of all BBCH stages. A positive MBE value indicates that, on average, the model overestimates actual observations; a negative value indicates that the model underestimates actual observations under specific annual or local conditions (Caffara & Eccel, 2010).

RESULTS

1. Phenological observation data

Days of the year (DOY) on which the phenological stages BBCH 01 to 89 were reached in the years 2021 to 2024 at the selected locations (complete data sets over four years) in the 16 cultivars of observation are shown in Table S3.

2. Cultivar specific temperature sum thresholds for the different phenological stages

Figure 2 shows the average $CDD_{10,20,30}$ threshold values relative to BBCH 09 in Riesling for the different cultivars. On average, the lowest $CDD_{10,20,30}$ value for BBCH 09 was recorded for Muscaris (–13) and the highest for Pinotin (3). The lowest $CDD_{10,20,30}$ value for BBCH 61 was observed for Solaris (195). Divico showed the lowest $CDD_{10,20,30}$ value for BBCH 81 (601), Solaris for BBCH 89 (797). For all those three stages highest values were observed for Riesling (BBCH 61: 251, BBCH 81: 859, BBCH 89: 1012) (Figure 2). Figure 3 displays graphically the differences between the different cultivars in $CDD_{10,20,30}$ values for the respective stages.

Lowest $SD_{15\,°C}$ values (except BBCH 09 for Riesling as reference) were observed in case of all stage × cultivar combinations for Muscaris at BBCH 11 (0.6 = 0.6 days at 15 °C) and highest for Riesling at BBCH 79 (19.2). On average of all cultivars, lowest $SD_{15\,°C}$ values were recorded for BBCH 09 (1.2) and highest for BBCH 79 (13.4). On average of all stages, the lowest $SD_{15\,°C}$ values were observed in Sauvignac (5.0) and the highest in Divico (6.7), with 5.5 being the average $SD_{15\,°C}$ value over all 16 cultivars (Figure 4).

Highest MBE values (recording later than simulated) were recorded in Cabernet Cortis in Geilweilerhof (20.1 $CDD_{10,20,30}$) and lowest (recording earlier than simulated) in Pinot noir in Marcelin (–21.4 $CDD_{10,20,30}$). On average of all cultivars highest MBEs were observed in case of Geilweilerhof (7.6 $CDD_{10,20,30}$) and lowest in case of Freiburg (–12.7 $CDD_{10,20,30}$).

Highest MAE values were observed for Pinot noir in Marcelin (23.1 $CDD_{10,20,30}$) and lowest for Sauvignac in Neustadt (7.0 $CDD_{10,20,30}$). Likewise, on average of all cultivars highest MAE values were reached in Marcelin (17.6 $CDD_{10,20,30}$) and lowest in Neustadt (10.2 $CDD_{10,20,30}$) (Table 4).

Concerning the vintage effect, highest MBE values were recorded in Muscaris in 2024 (12.9 $CDD_{10,20,30}$) and lowest in Regent in 2021 (–23.0 $CDD_{10,20,30}$). On average of all cultivars, highest MBE were observed in 2023 (7.3 $CDD_{10,20,30}$) and lowest in 2021 (–11.9 $CDD_{10,20,30}$). In 2021, the MBE values of all cultivars were negative.

Highest MAE values were observed for Regent in 2023 (25.1) and lowest for Calardis blanc in 2022 (7.0 $CDD_{10,20,30}$). On average of all cultivars highest MAE values were recorded for 2021 (16.3 $CDD_{10,20,30}$) and lowest for 2022 (9.7 $CDD_{10,20,30}$) (Table 5).

DISCUSSION

1. Model application for PIWI cultivars

The application of the UniPhen for 13 PIWI cultivars based on at least eight observation data sets revealed the average $CDD_{10,20,30}$ thresholds relative to BBCH 09 in Riesling until

BBCH	Cabernet blanc	Cabernet Cortis	Cabertin	Calardis blanc	Johanniter	Monarch	Muscaris	Pinotin	Regent	Sauvignac	Solaris	Souvignier gris	Divico	Müller-Thurgau	Pinot noir	Riesling
01	-28	-37	-23	-30	-33	-30	-34	-23	-31	-30	-36	-35	-33	-34	-31	-27
03	-21	-30	-18	-23	-29	-27	-29	-18	-25	-23	-30	-29	-26	-27	-24	-20
05	-15	-24	-15	-18	-25	-22	-25	-12	-22	-18	-25	-22	-21	-21	-19	-16
07	-7	-14	-7	-12	-18	-16	-19	-5	-15	-12	-17	-13	-15	-15	-13	-8
09	-1	-7	3	-3	-7	-5	-13	3	-5	-6	-10	-6	-7	-6	-6	0
11	11	5	14	13	6	12	1	15	9	5	5	4	5	3	4	13
12	22	17	25	24	15	24	12	26	21	15	15	14	15	12	12	23
13	33	28	38	37	29	38	20	41	32	26	27	25	25	22	25	33
14	50	43	53	55	46	53	34	53	52	41	45	41	38	35	39	48
15	65	60	73	78	68	70	51	73	71	55	59	63	50	52	56	67
16	88	84	100	103	92	89	65	100	92	72	78	92	67	71	76	89
17	111	109	123	130	112	109	86	128	114	95	102	112	93	96	97	108
18	133	133	150	154	139	130	106	157	137	118	121	136	113	119	119	128
19	155	162	176	179	166	150	128	182	162	139	146	162	144	144	145	152
53	74	46	92	67	65	55	45	96	65	61	48	54	45	51	56	75
55	125	97	145	118	123	109	101	153	124	110	88	104	73	109	101	130
57	200	158	212	176	199	169	163	217	187	186	140	175	154	182	179	196
61	247	207	248	211	231	223	203	250	222	227	195	223	201	230	225	251
63	261	220	260	231	246	252	223	265	246	242	212	241	219	246	244	267
65	275	233	271	247	267	265	244	277	269	256	228	256	237	262	264	281
68	295	264	292	265	286	283	262	292	289	272	248	270	252	278	278	297
69	317	281	314	284	305	296	276	317	320	287	266	285	264	292	296	317
71	348	304	345	312	321	336	298	346	347	311	287	305	283	318	319	342
73	391	359	385	358	350	396	343	382	380	351	327	352	333	361	361	383
75	472	426	462	433	408	451	403	464	457	412	389	422	382	424	428	473
77	617	476	544	515	479	528	492	554	515	492	451	506	490	520	503	522
79	757	577	683	660	574	628	600	678	629	637	544	618	555	628	603	606
81	815	663	721	772	726	686	737	697	679	764	604	763	601	730	775	859
83	860	727	771	823	780	772	792	756	761	823	659	817	679	775	835	894
85	889	787	812	864	817	836	828	803	808	857	705	861	748	816	875	926
89	972	879	879	972	908	926	908	945	880	961	797	951	883	928	960	1012

FIGURE 2. Heat map of the average $CDD_{10,20,30}$ values relative to BBCH 09 in Riesling until the respective BBCH stage was reached in the 16 cultivars of investigation. Negative values indicate that the respective BBCH stage has been reached prior to BBCH 09 in Riesling. In each BBCH stage, the cultivar with the lowest $CDD_{10,20,30}$ value (= earliest development) is depicted in green and the cultivar with the highest $CDD_{10,20,30}$ value (= latest development) in red. Intermediate values are presented in graduated colours between dark green and dark red.

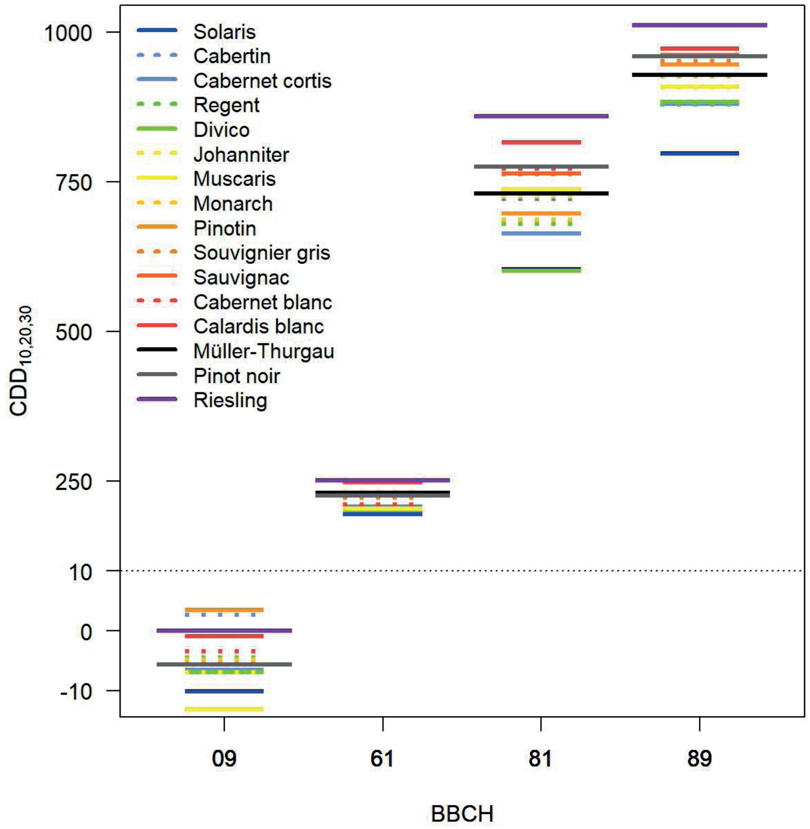

FIGURE 3. $CDD_{10,20,30}$ values relative to BBCH 09 in Riesling until the BBCH stages 09, 61, 81 and 89 were reached in the 16 cultivars of investigation. Please note that the scale is differing between BBCH 09 and the other three stages.

BBCH	Cabernet blanc	Cabernet Cortis	Cabertin	Calardis blanc	Johanniter	Monarch	Muscaris	Pinotin	Regent	Sauvignac	Solaris	S. gris	Divico	Müller-Thurgau	Pinot noir	Riesling	Average
01	2.7	2.1	2.7	2.8	2.6	2.7	2.0	2.7	3.3	2.6	2.0	2.5	2.7	2.5	2.5	2.5	2.6
03	2.3	2.2	2.5	2.5	2.7	2.6	2.5	2.4	3.2	2.8	2.4	2.5	2.6	2.3	2.6	2.1	2.5
05	2.1	1.8	2.2	2.2	2.5	2.0	2.5	2.1	3.3	2.3	2.0	2.0	2.6	2.1	2.1	2.0	2.2
07	1.2	1.5	1.6	2.1	2.1	2.1	2.1	1.3	2.4	1.6	1.9	1.7	2.2	1.9	2.0	1.5	1.8
09	0.8	1.4	1.7	1.3	1.3	0.9	1.9	1.1	1.5	1.0	1.6	1.0	1.7	1.1	1.2	0.0	1.2
11	1.6	1.9	2.3	1.6	1.4	1.4	0.6	1.9	2.8	1.5	1.5	1.0	1.6	1.3	1.2	1.3	1.6
12	1.8	2.3	2.3	2.1	1.9	1.9	1.6	1.8	3.0	2.3	2.1	1.6	1.7	1.7	1.9	2.4	2.0
13	1.7	3.1	2.6	2.8	2.2	2.5	2.0	2.4	2.7	2.7	2.5	2.0	1.9	1.8	2.1	2.6	2.4
14	1.7	4.0	2.2	3.1	2.9	2.5	2.2	2.8	2.4	2.9	3.8	2.0	2.8	2.3	2.8	2.7	2.7
15	2.0	3.6	2.8	3.0	2.0	2.8	2.4	2.3	1.6	2.8	3.2	2.9	3.6	2.5	3.1	2.9	2.7
16	2.7	3.6	3.2	3.8	2.6	4.0	2.4	2.1	2.3	3.4	3.7	2.9	4.9	2.9	3.6	3.6	3.2
17	2.7	3.9	3.3	3.6	3.6	4.8	3.5	3.6	3.4	3.3	4.2	2.7	5.2	3.0	4.1	3.8	3.7
18	3.3	4.8	4.4	4.6	5.1	6.2	3.8	5.0	3.3	3.2	4.5	3.3	5.2	3.4	3.9	4.1	4.3
19	4.8	5.6	4.4	4.1	5.2	7.1	4.6	5.0	4.0	4.0	5.0	4.6	4.2	4.7	4.7	5.2	4.8
53	5.9	5.1	5.8	7.5	3.5	3.9	4.8	5.4	3.4	5.2	5.2	4.9	6.1	4.9	5.4	4.5	5.1
55	6.4	9.6	5.7	5.9	4.5	4.4	5.7	5.4	5.5	6.2	5.7	5.5	5.1	6.0	7.4	4.6	5.8
57	4.9	8.7	4.7	6.8	7.2	9.4	7.3	4.7	8.4	4.5	5.3	6.2	9.3	4.9	7.3	5.6	6.6
61	4.1	5.0	3.9	5.3	4.5	6.1	4.8	4.5	8.2	4.7	3.8	5.3	6.6	4.3	7.0	3.7	5.1
63	4.2	7.4	4.1	4.8	4.2	4.9	4.7	4.3	6.4	4.9	3.9	4.4	4.6	4.1	4.9	3.6	4.7
65	4.2	7.2	4.1	4.7	4.3	5.2	4.7	4.6	5.3	4.8	4.7	5.3	4.7	4.1	4.9	3.7	4.8
68	5.2	6.6	5.2	5.6	5.1	4.2	4.5	5.0	5.7	4.5	5.2	5.4	5.1	5.4	5.5	4.0	5.1
69	6.5	6.0	6.4	6.4	5.1	4.1	4.9	6.7	8.0	4.6	5.0	4.9	5.7	4.9	5.5	5.0	5.6
71	7.9	6.6	7.6	7.4	5.2	3.9	6.1	7.6	8.7	5.0	5.1	5.4	5.4	6.0	5.9	6.0	6.2
73	8.4	8.2	7.0	6.8	5.9	5.6	6.4	7.6	8.2	7.9	6.5	8.4	6.0	7.1	7.8	7.4	7.2
75	6.1	8.1	5.8	6.2	5.4	10.5	6.2	5.3	8.1	6.4	6.9	9.4	7.4	7.9	9.4	8.1	7.3
77	17.7	9.1	7.7	8.7	11.0	10.0	9.0	8.7	11.4	7.0	8.1	13.3	17.6	11.8	11.5	14.1	11.1
79	16.6	14.6	10.1	14.1	11.9	8.3	14.1	9.4	5.2	14.6	11.9	16.7	17.6	11.8	15.6	19.2	13.4
81	9.8	9.8	8.2	6.2	9.4	8.4	12.2	7.8	8.3	9.5	9.0	11.0	18.5	10.2	15.2	9.0	10.2
83	7.8	10.0	9.1	8.8	9.8	8.6	8.1	7.9	12.0	7.5	11.6	11.5	17.4	10.2	11.5	9.4	10.0
85	8.3	10.3	9.8	9.4	12.4	11.3	9.5	11.4	9.3	9.4	12.5	10.3	10.6	11.2	11.6	11.0	10.5
89	10.9	16.3	12.7	13.9	12.4	13.8	11.4	13.3	14.9	11.6	16.0	12.7	17.3	14.0	12.9	9.4	13.3
Average	5.4	6.1	5.0	5.4	5.2	5.4	5.1	5.0	5.7	5.0	5.4	5.7	6.7	5.2	6.0	5.3	5.5

FIGURE 4. Heat map of the normalised standard deviation at 15 °C ($SD_{15\,°C}$) in the 16 cultivars in the different stages as well as on average of all stages. Over all stages and cultivars, the cultivar × stage combination with the lowest $SD_{15\,°C}$ value (= lowest deviation) is depicted in green and the cultivar × stage combination with the highest value (= highest deviation) in red. Intermediate values are presented in graduated colours between dark green and dark red.

TABLE 4. Average mean bias errors (MBE) and mean absolute errors (MAE) on average of all stages (BBCH 01 to 89) in the different locations in all cultivars.

	MBE								MAE							
Cultivar	**Re**	**Gf**	**At**	**Ma**	**Ki**	**Nw**	**Fr**	**Eb**	**Re**	**Gf**	**At**	**Ma**	**Ki**	**Nw**	**Fr**	**Eb**
Cabernet blanc	1.3	1.1			–4.8	9.1		–6.7	11.8	8.8			9.2	10.6		15.7
Cabernet Cortis		20.1	–10.2				–16.7	6.8		20.6	14.2				16.7	11.8
Cabertin	–11.3	10.2				1.1			14.3	13.3				8.2		
Calardis blanc	–6.3	10.9				10.9	–15.4		14.3	14.5				13.0	15.4	
Johanniter	–3.9	3.5	0.4						7.9	10.0	9.5					
Monarch		6.8	–6.8							8.9	8.9					
Muscaris	–0.3	4.8	–6.3			1.9			7.9	12.8	11.7			10.0		
Pinotin	–8.4	5.1				3.3			14.3	9.4				10.8		
Regent		7.8	–7.8							10.4	10.4					
Sauvignac	–9.2	4.7			–6.6	2.9		8.2	15.2	7.7			9.4	7.0		15.8
Solaris	2.0	10.7	–10.8			2.0	–14.9	11.1	9.3	13.2	11.3			10.6	15.1	12.2
Souvignier gris	6.4		9.5		–3.4		–18.4	5.9	13.3		14.9		9.3		18.6	13.6
Divico	7.3			–3.2			–4.0		13.4			12.0			12.8	
Müller-Thurgau	5.3	5.0	4.7		–11.0		–10.9	6.8	12.4	12.5	13.5		12.9		12.4	11.1
Pinot noir	–0.2	10.3	5.6	–21.4	–6.0	12.6	–8.7	7.7	15.1	12.8	14.2	23.1	9.3	13.0	16.1	11.5
Riesling	1.1	6.0	8.5		–14.4	–1.2			8.0	12.6	18.4		15.6	8.2		
Average	–1.2	7.6	–1.3	–12.3	–7.7	4.7	–12.7	5.7	12.1	12.0	12.7	17.6	11.0	10.2	15.3	13.1

the respective BBCH stage is reached per cultivar. It allows for a classification of the relative precocity of all 13 PIWI cultivars (plus three traditional reference cultivars) in each of the 31 stages of the BBCH scale between 01 and 89. As described before (Molitor *et al.,* 2020), the relative precocity of the different cultivars is not stable over the different phenological stages, for example, Calardis blanc is one of the latest cultivars in leaf development, while one of the earliest in beginning of flowering and again the latest PIWI cultivar to reach harvest maturity (Figure 2). According to their precocity in budburst, Muscaris and Solaris could be classified as "early" while Pinotin and Cabertin are rather late, even slightly later than the traditional reference Riesling (consequences are discussed in the paragraph Practical applications).

The present investigations confirmed the general suitability of the cumulative degree day approach using three threshold temperatures as proposed first by Molitor *et al.* (2014b) and unified later by the introduction of the optimised temperature sum threshold triplet 10, 20 and 30 °C in the UniPhen approach (Molitor *et al.,* 2020). Observed global average normalised standard deviations correspond to 5.5 days at 15 °C (or 2.75 days at 20 °C) demonstrating the strong robustness of the UniPhen model also for the PIWI cultivars.

Generally, for all cultivars, normalised standard deviations $SD_{15\,°C}$ are lowest around budburst. In this period normalised standard deviations correspond to 1 to 2 days, indicating the high model precision. While in stages of inflorescence emergence standard deviations slightly increase, during flowering (BBCH 61-69) and fruit-set (BBCH 71) the $SD_{15\,°C}$ values correspond to standard deviations of less than 6 days. As described before (Molitor *et al.,* 2020) for traditional cultivars, higher average normalised standard deviations were observed in the bunch closure stages 77 and 79. Here, as well as in the stages of inflorescence emergence the perception of the observer is more subjective than in case of leaf emergence or flowering (Verdugo-Vasquez *et al.,* 2017). Furthermore, the degree of fruit set, water and nutrient availability, as well as the yield potential have an influence on the cluster architecture and, in consequence, the moment of fruit set. Standard deviations corresponding to 13.3 days at 15 °C were observed for stage BBCH 89. These standard deviations can partly be explained by the observation intervals (7 days (weekly maturity control) versus 2–3 days

TABLE 5. Average mean bias errors (MBE) and mean absolute errors (MAE) on average of all stages (BBCH 01 to 89) in the different years in all cultivars.

	MBE				MAE			
Cultivar	**2021**	**2022**	**2023**	**2024**	**2021**	**2022**	**2023**	**2024**
Cabernet blanc	–14.2	0.0	5.1	9.1	18.6	7.9	9.3	12.6
Cabernet Cortis	–15.7	1.0	9.2	5.5	18.5	9.0	11.8	11.5
Cabertin	–10.8	3.4	3.7	3.7	19.7	11.6	7.8	11.8
Calardis blanc	–5.8	–2.7	11.0	–2.6	12.1	7.0	12.1	7.6
Johanniter	–11.8	1.8	12.5	–2.5	15.2	9.0	12.6	11.7
Monarch	–14.4	5.1	7.2	2.2	18.3	11.3	8.1	12.6
Muscaris	–15.4	–4.0	6.6	12.9	18.4	8.4	8.3	16.1
Pinotin	–13.3	–1.0	13.5	0.8	19.8	8.2	14.4	12.4
Regent	–23.0	11.3	8.4	3.3	25.1	12.4	13.8	15.8
Sauvignac	–8.3	–8.1	8.2	8.1	11.4	10.6	12.8	11.8
Solaris	–7.3	–7.4	6.6	8.1	12.0	9.3	7.8	12.4
Souvignier gris	–5.3	–2.6	–4.6	12.5	8.7	8.5	12.3	18.6
Divico	–3.3	–10.4	8.0	5.7	12.3	15.0	16.1	10.1
Müller-Thurgau	–14.3	2.8	7.8	3.7	16.8	8.7	9.6	8.9
Pinot noir	–12.6	–4.0	8.4	8.2	15.4	8.6	11.6	11.5
Riesling	–15.7	2.2	4.8	8.8	17.9	9.1	8.0	12.4
Average	–11.9	0.8	7.3	5.5	16.3	9.7	11.0	12.4

for the other stages) as well as annual differences in sugar accumulation caused by differences in crop load (Santesteban & Royo, 2006).

The effects of the locations as well as the vintages were evaluated using the mean bias error and the mean average error. While in Geilweilerhof on average of all years and cultivars the stages were recorded 7.6 $CDD_{10,20,30}$ later than simulated, for Freiburg this was the case 12.7 $CDD_{10,20,30}$ earlier (corresponding to 2 to 3 days at 15 °C). These minor effects might be explained by the differences in the perception of the observers or potentially micro-climatic effects caused by the position of the weather station relative to the vineyard of observation. Observed average mean average errors at the different locations between 10.2 $CDD_{10,20,30}$ in Neustadt and 17.6 $CDD_{10,20,30}$ in Marcelin might be reasoned by differences in the observation interval or the consistency of the observations.

Interestingly, concerning the deviations caused by the vintage, all cultivars showed in 2021 a negative mean bias error, meaning that all stages were on average earlier observed than simulated, with deviations corresponding to an average of 2 days at 15 °C. While this deviation of 2 days might be acceptable in the application of the model, this systematicity might have its origin in the consistently lower temperatures in 2021 compared to the two following years and/or non-linear dependencies between the temperatures recorded by the weather stations and the apparent temperatures in the vineyard canopy.

2. Practical applications

Generally, the UniPhen approach is designed to allow the simulation of phenological phases, where environmental conditions or crop cultural measures, for example, have a distinct influence on factors such as yield formation (Molitor & Keller, 2016), wine typicity (Molitor & Junk, 2019) or susceptibility towards pests or diseases (Molitor *et al.,* 2016; Molitor *et al.,* 2020).

Usually, PIWI cultivars are not completely resistant against fungal infections, but of (i) lower susceptibility and/or (ii) their period of susceptibility of specific organs is shorter than in traditional cultivars since ontogenetic resistance appears phenologically earlier. Frequently, a limited number of fungicide applications in PIWI cultivars is recommended in the period of highest susceptibility for berry infections (Schumacher *et al.,* 2024). Periods of highest susceptibility, however, differ in their length between different PIWI cultivars, for example, Cabernet Cortis and Solaris are susceptible towards *Plasmopara viticola* until BBCH 71-73, whereas Souvignier gris is still susceptible at BBCH 75 (Schumacher *et al.,* 2024). Hence, simulating the phenological development supports a more targeted timing of fungicide treatments in PIWIs depending on their phenology driven status of susceptibility. The knowledge about the phenological status of different PIWI cultivars potentially contributes to a further reduction of pesticide use if applications outside the period of susceptibility are abandoned, for example, some PIWI cultivars might need to be treated at a specific point in time while other cultivars passed already their cultivar specific phenological growth stage of ontogenetic resistance. Here, the combination of the knowledge of cultivar-specific phases of susceptibility with UniPhen "PIWI" might deliver valuable decision support for users.

The obtained classification of relative cultivar precocity at different stages opens new chances for cultivar selection under practical conditions, especially in regions where late frost damage might constitute a serious threat for sustainable wine production (*e.g.*, Kartschall *et al.,* 2015; Leolini *et al.,* 2018; Molitor *et al.,* 2014a; Mosedale *et al.,* 2015), such as in many cool-climate viticulture regions including the new winegrowing regions emerging in recent years. Especially in these regions, PIWIs are frequently the cultivars of choice due to their reduced susceptibility as well as the missing customer's habit to prefer traditional cultivars. Under high late frost risk conditions cultivars with early bud development and early bud burst might be avoided based on the information derived from the present model.

Solaris and Muscaris were identified as thermal-temporally early in budburst and, hence, more likely to be damaged by late frost events at dates where other cultivars are not yet susceptible, since green shoots and leaves have not yet emerged. Taking into consideration a long-term average (1991–2020) April to May (period where late frost damage takes place) temperature in Remich of 12.4 °C, the observed difference of 10 (Solaris) or even 13 (Muscaris) $CDD_{10,20,30}$ compared to Riesling could be translated to a precocity of four days for budburst and, hence, a four or five days longer risk period for late frost damage. This fact should be considered when thinking about cultivar selection in regions or locations where late frost damage is likely. Concerning the late frost damage risk, Pinotin or Cabertin might be interesting candidates since they are the only PIWI cultivars with a slightly later budburst than the traditional reference cultivar Riesling. Indeed, under cool climate conditions such as in the newly emerging Northern European grape growing region, the ideotype of a PIWI would be one that exhibits a late/delayed bud burst combined with an early full maturity. In fact, the observations as well as the methodology of the present paper could also be useful for breeders in selecting parental material for the breeding of new cultivars with those ideal characteristics.

Generally, PIWI cultivars could potentially pave the way for long-term adaptation strategies to achieve higher climate resilience (Terleth & Tavernar, 2022; Tscholl *et al.,* 2024). Consequently, the percentage of PIWI cultivars in new plantations is increasing in recent years – especially, but not exclusively, in the new winegrowing regions and at higher altitudes, which have in past not been suitable for viticulture due to limited heat consumption. However, so far little was known about the cultivar specific heat demand of PIWI cultivars to produce grapes with adequate maturity for wines of high quality. The BBCH scale defined the stage BBCH 89 as "berries ripe for harvest". Hence, the temperature sum necessary to reach BBCH 89 is linked to the annual heat demand for a specific cultivar to produce fully mature grapes. Using UniPhen "PIWI" as a bioclimatic indicator allows to describe the suitability of different locations or altitudes for the cultivation of specific cultivars under changing climatic conditions.

Especially the classification of relative precocity of the maturity period (BBCH 81-89) might be used for the selection of PIWI cultivars in climate change adaptation strategies. Particularly high temperatures in the maturation period have been demonstrated to negatively affect wine fruitiness and its aroma (Duchêne *et al.,* 2010). Consequently, PIWI cultivars with a thermal-temporally early ripening period leading to hot temperatures during maturation such as Solaris should be avoided in the traditional Central European wine growing regions – especially since a twofold increase of the ripening period temperatures is expected with ongoing climate change (Molitor & Junk, 2019). On the other hand, early ripening PIWI cultivars are of highest interest for cool winegrowing regions outside the traditional regions as well for viticulture at higher altitudes. Here, it is recommended to check prior to the planting of a vineyard if the annual heat consumption of a region or location fits to the heat demand of the cultivar of interest. The information about the general suitability of cultivars for cultivation under specific climatic conditions can be derived from UniPhen "PIWI". Based on long-term observation data, (i) virtual dates of reaching specific phenological stages as well as $CDD_{10,20,30}$ values at the end of the season can be calculated and (ii) potentially fitting cultivars might be selected, for example, if the $CDD_{10,20,30}$ value at the end of the season reaches 800, only Solaris might be a suitable candidate out of the 13 PIWI cultivars tested here. Since the cultivar selections are long-term decisions, additionally, future climate projections might be incorporated to simulate the future heat consumption for a specific region.

Generally, the observed systematic biases caused by the location were low and might be caused by differences in the perception of the observers. The observed mean bias errors between –12.7 and 7.6 $CDD_{10,20,30}$ refer to less than 3 days earlier or less than 2 days later observations than simulated, respectively. Consequently, the model proved to be valid under present Central European conditions. Under completely different climatic conditions, the model may need to be validated first with local observation data before being applied. However, the chance that cultivars with heat demands corresponding to the conditions in Central Europe (as the present ones), might be cultivated under clearly hotter conditions appears unlikely. Generally, it must be taken into consideration that extreme weather events, like late frost damage or hailstorm damage, destroying the green plant tissues, might lead to a temporary stop or even a reset of the phenological development. In such cases the model might not be applicable.

CONCLUSIONS

Based on a broad set of observation data, the UniPhen model was applied and allows now for a precise simulation of all 31 BBCH stages between the beginning of bud swell (01) and berries ripe for harvest (89) for 13 PIWI cultivars. UniPhen "PIWI" could be used (i) to simulate periods of highest susceptibility towards fungal diseases and contribute to reduce fungicide use to a minimum as well as (ii) a bioclimatic indicator for the suitability of a location/region for the cultivation of specific PIWI cultivars, considering late frost risk and minimum heat demand to produce high quality wines. Present data and the model itself might help to alleviate lowering the existing barriers for grape growers (due to a lack of experience and knowledge) to grow these alternatives to traditional, susceptible cultivars.

UniPhen "PIWI" as well as the UniPhen approach in general is open to be extended for other grape cultivars and application under different or future climatic conditions.

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