

## Grapevine phenology in France : from past observations to future evolutions in the context of climate change

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*This article is published in cooperation  
with the ClimWine international conference held in Bordeaux 11-13 April 2016.  
Guest editor: Nathalie Ollat*

### Abstract

**Aim :** Phenology is a key factor in explaining the distribution and diversity of current vineyards in France. This work has the objective to summarize the different studies developed in France to analyze grapevine phenology.

**Methods and results :** Several topics are presented : a general description of all historical databases and observatory networks developed in France during the last 70 years ; an overview of the different models developed to calculate the main phenological stages ; an analysis of the main results obtained using these models in the context of studies of climate change impacts on viticulture in France ; and finally a general discussion about the main strategies to adapt the phenological cycle to future climate conditions.

**Conclusion :** This review emphasizes that even if phenology is not the only trait to be considered for adapting grapevine to climate change, it plays a major role in the distribution of the current variety x vineyard associations.

**Significance and impact of the study :** It is therefore critical to continue to study phenology in order to better understand its physiological and genetic basis and to define the best strategies to adapt to future climatic conditions.

**Keywords :** *Vitis vinifera* L., phenology, climate change, dataset, model, observation, France, cultivar

*Received : 9 September 2016; Accepted : 4 November 2016  
DOI: 10.20870/oeno-one.2016.0.0.1622*

**Table 1. Classification of the phenological timing of the 43 cultivars covering 95 % of the French vineyards.**

Five groups of phenological timing were defined using F\* values ([1120 - 1411] and [2286 - 2941] for flowering and veraison, respectively) calculated using the GFV model (Parker *et al.*, 2013). Note there are no French vineyard varieties in the Very Early or Very Late classes based on the data published in Parker *et al.* (2013). Groups were built assuming a normal distribution of the F\* value and calculating different percentage values.

Phenology class	% F* range	Flowering			Veraison		
		Range of F* values (based on GFV model in Parker <i>et al.</i> , 2013)	Number of varieties	Varieties	Range of F* values (based on GFV model in Parker <i>et al.</i> , 2013)	Number of varieties	Varieties
Very Early	< 5%	< 1134	1	Meunier	< 2318	0	-
	5 - 25%	1134 - 1192	1	Pinot gris	2318 - 2449	1	Meunier
	25 - 75%	1192 - 1338	36	Alicante Bouschet, Aligoté, Aramon, Auverrois, Cabernet franc, Cabernet-Sauvignon, Carignan, Chardonnay, Chenin, Cinsaut, Clairette, Colombar, Cot, Gamay, Gewurstraminer, Grenache, Grenache blanc, Grenache gris, Grolleau, Gros Manseng, Macabeu, Marselan, Mauzac, Melon, Merlot, Muscat à petits grains, Nielluccio, Pinot noir, Piquepoul blanc, Riesling, Roussanne, Sauvignon, Semillon, Syrah, Vermentino, Viognier	2449 - 2777	38	Alicante Bouschet, Aligoté, Aramon, Auverrois, Cabernet franc, Cabernet-Sauvignon, Carignan, Chardonnay, Chenin, Cinsaut, Clairette, Colombar, Cot, Gamay, Gewurstraminer, Grenache, Grenache blanc, Grenache gris, Grolleau, Macabeu, Marselan, Mauzac, Melon, Merlot, Mourvèdre, Muscat à petits grains, Muscat d'Alexandrie, Nielluccio, Pinot noir, Pinot gris, Piquepoul blanc, Riesling, Roussanne, Sauvignon, Semillon, Syrah, Vermentino, Viognier
Late	75 - 95%	1338 - 1396	5	Caladoc, Mourvèdre, Muscat d'Alexandrie, Tannat, Ugni Blanc,	2777 - 2908	4	Caladoc, Gros Manseng, Tannat, Ugni blanc
Very Late	> 95%	> 1396	0	-	> 2908	0	-

## Introduction

Phenology is the study of recurring plant and animal life cycle stages in relation to weather and climate (Schwartz, 2013). As for many other crops, grapevine phenology studies have been largely reported in the literature (see Coombe, 1995 and Jones, 2013 for a review). Usually, winegrowers use this information to 1) choose the variety that is more suitable to their vineyard and 2) adapt their practices (i. e. fertilization, topping) to variations in climatic conditions in space (among vineyards) and in time (among vintages).

Phenology is considered as the first biological indicator of climate change (Menzel *et al.*, 2006). In the past, the three main grapevine phenological stages (budbreak, flowering, veraison) and the harvest dates have been used to quantify the magnitude of climate change in several vineyards over the world (Jones *et al.*, 2005). In this context, phenology is also described as one of the main factors to be explored for varietal adaptation (Duchêne *et al.*, 2010).

Grapevine diversity is large, representing 5000 – 10000 cultivars of *Vitis vinifera* L. (Lacombe *et al.*, 2013). Phenological diversity of this species is particularly high and has been addressed in several studies quantifying and describing the existing variability for this trait at the species level (Boursiquot *et al.*, 1995, Parker *et al.*, 2013).

Currently in France it is possible to cultivate 347 varieties for fruit production (wine grape and table grape). However, only 10 varieties (Merlot, Grenache, Ugni blanc, Syrah, Cabernet-Sauvignon, Chardonnay, Carignan, Cabernet franc, Pinot noir and Sauvignon) represent 71.7 % of the total surface area of planted vines (FranceAgriMer, 2014), and only 43 varieties cover 95 % of the total vineyard surface area in France (800.000 ha). In accordance with the classification provided by Parker *et al.* (2013), most of these 43 varieties can be classified in the medium category class in terms of timing of flowering and veraison (Table 1). “Very early” and “very late” phenology classes are underrepresented or not represented at all. This rapid analysis shows that the current available biodiversity for phenology requires further investigation (for example varieties covering the remaining 5 % of the total surface).

The objective of this research summary is to review the different studies developed in France to analyze grapevine phenology. The summary is separated in two main sections: 1) an overview of the work achieved to date using historical databases and different models developed to calculate the main phenological stages; and 2) a general discussion of

the main strategies investigated to adapt the phenological cycle to future climate conditions.

## Historical observations, databases and observatories

In France there is a long tradition of observing grapevine phenology. Several comprehensive phenological databases have been established over the past 35 years as a result of the extensive collection of diverse phenological data from a range of sites and years.

Multiple grapevine observatories have been implemented in different INRA (French national institute of agronomical research) centers in Bordeaux, Angers, Colmar and Montpellier. In each of these sites, several local varieties (for example Chenin in Angers, Gewürztraminer and Riesling in Colmar) as well as varieties imported from other regions of France (for example Cabernet-Sauvignon in Colmar) have been monitored over several years, in some cases since the 1950s. Near Montpellier, the Domaine de Vassal germplasm repository ([www6.montpellier.inra.fr/vassal/](http://www6.montpellier.inra.fr/vassal/)), which includes more than 2700 cultivars of *Vitis vinifera* L., was set up in the 1950s, and since then, key stages of phenology have been monitored annually for a number of varieties. All these data have been collected and stored by different methods and by different teams in the last 70 years.

In this context, by the early 2000s, several information systems and databases have been developed in France in order to store, structure and centralize phenological data. In 2002, the PHENOCLIM database was created by INRA in order to compile the historical observed data from main varieties of perennial crops studied at INRA and in other technical institutes. The analysis of this database has highlighted the importance of these historical datasets to study past climate evolution (Domergue *et al.*, 2003). In parallel and for the scientific community working on genetics and genomics, the EPHESES database, for Environment and Phenotype Information System, has been developed. This module of the GNPIS platform (<https://urgi.versailles.inra.fr/gnpis/>) is dedicated to the integration of experimental trials on genotype by environment studies (Steinbach *et al.*, 2013). Any data pertaining to phenotypic traits, including plant phenology, can be stored and link to genetic data in this database. Currently, data from cultivar repositories of different experimental sites are integrated in this platform. Another system, the VITPHE database, for Vitis Phenotyping, was also developed in Montpellier and Bordeaux to provide a

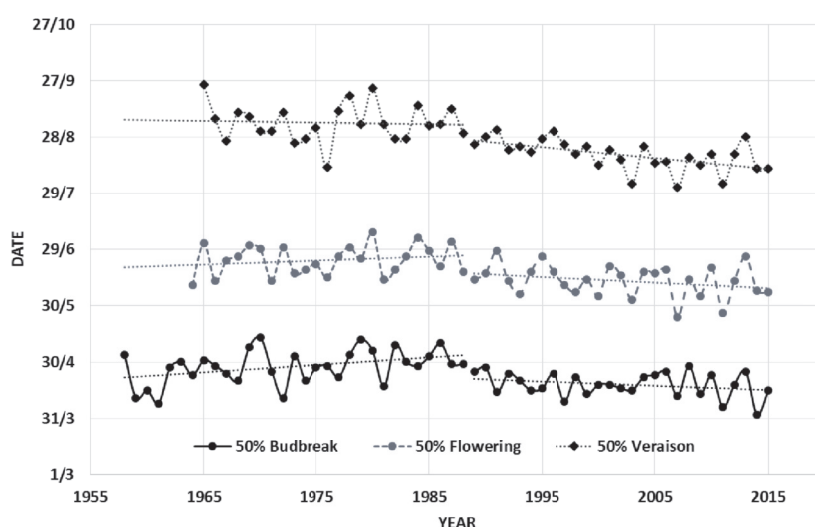
useful resource for the scientific community working on plant phenotyping and genotype  $\times$  environment interactions in grapevine (<http://bioweb.supagro.inra.fr/vitphe/public/>). Under the framework of citizen science actions developed in France, the database “Observatoire des Saisons” (<http://www.obs-saisons.fr/>) has been operating since 2006 to collect phenology data for a wide range of species, including not just cultivated species but also wild and forest species. Finally, since 2016, an interconnection system of phenology databases was developed in the framework of the PERPHECLIM project ([w3.avignon.inra.fr/perpheclim/](http://w3.avignon.inra.fr/perpheclim/)). This system allows the user to access all the databases described above and to obtain a global overview of the existing data for any given species in the database (in the case of this research, for grapevine).

From these databases and observatories, research studies have illustrated changes in the phenology of several grape varieties in the recent decades, particularly in connection with the increase of temperature. A pioneer study of the relationship between phenology and current climate evolution was carried out by Duchêne and Schneider (2005) analyzing the Riesling dataset from Colmar (Figure 1).

In this series, the authors showed that the main phenological stages (mid-budbreak, mid-flowering and mid-veraison) have advanced significantly over the last 50 years. There has been a change in interannual variability depending on the considered phenological stage: for the 1989-2015 period,

interannual variability increased for flowering compared with the 1958-1988 period, but for budburst and veraison the interannual variability decreased for the 1989-2015 period (compared with 1958-1988). These changes and trends did not occur only in the Alsace region (see for example the climatic analysis for the Burgundy region in Richard *et al.*, 2014), but have been observed in almost all French vineyards (data not shown) and in many other vineyards in the world (Jones *et al.*, 2005). All these observations combined with flowering data from other fruit species (i. e. apple blooming data shown by Legave *et al.*, 2013) emphasize the importance of phenological data as an indicator of past climate evolution. This study has also highlighted the necessity of a more comprehensive research to understand the adaptability of crops to climate change.

In the past 15 years, grapevine harvest dates have been used to study past climate evolution. Even if harvest dates cannot be considered as a phenological stage, they have been successfully used as a proxy in past climate studies (Chuine *et al.*, 2004, Menzel, 2005, Meier *et al.*, 2007, Etien *et al.*, 2008, 2009, Yiou *et al.*, 2012, Cook and Wolkovich, 2016). A database was published by Daux *et al.* (2012) with approximately 350 datasets totaling approximately 17000 harvest dates from 22 vineyards covering the 1354-2007 period. The studies based on this dataset have shown that reconstructed temperature anomalies correlated well with other temperature proxies (i. e. tree rings) and the dataset corresponded



**Figure 1. Evolution of the main phenological stages (50 % budbreak, 50 % flowering, 50 % veraison) of the Riesling cultivar in Alsace (Bergheim) over the past 60 years.**

Data from INRA - Colmar. Trend curves have been added in order to show the breaking point in 1988-1989 as described in the text. The variability is significantly lower in the last 30 years compared with the preceding time period for 50 % budbreak and 50 % veraison stages (9 days vs 6.5 days and 10 days vs 8.2 days, respectively) and slightly higher for 50 % flowering (8 days vs 8.5 days).

to and confirmed the documented temperature anomalies, in particular in long time series (García de Cortázar-Atauri *et al.*, 2010b). Nevertheless, different factors playing a role in the choice of the harvest date (for example variety, wine style, training system, etc.) may have generated more variability in harvest dates over the past four decades. Therefore, it may be important to identify and characterize the uncertainties in climate reconstructions generated by these potentially confounding factors in more recent time series (van Leeuwen and Darriet, 2016).

Faced with the challenges of climate change, new experimental platforms have also emerged in recent years to characterize several traits (including phenology) of grapevines. This is notably the objective of the VITADAPT field experiment at INRA-ISVV in Bordeaux. This experimental system includes 52 *V. vinifera* varieties from different French vineyards and other countries, covering a very large range of precocity. The objective of the VITADAPT project is to characterize this group of varieties and study their suitability to the changing climatic conditions of the Bordeaux area (Figure 2).

Finally, with the objective to breed new grapevine varieties better adapted to future climatic conditions, many teams are studying the genetic basis of

phenology (Grzeskowiak *et al.*, 2013, Fechter *et al.*, 2014). For example, Duchêne *et al.* (2012) have characterized the genetic variability created in the progeny of a cross between Riesling and Gewürztraminer (Figure 3). Their results showed that some regions in the grapevine genome are linked to the observed variation in phenology. These regions encompass specific genes that could participate to the genetic variability of grapevine phenology.

The current infrastructures, observatories, information systems, databases and scientific projects have led to the development of a global framework that can be used in future studies to investigate the impacts of climate change on phenology and to define future adaptation strategies.

### Phenological process-based models

Phenology modeling has been widely developed for many different species in the last 50 years (Chuine *et al.*, 2013). In this context, several phenological process-based models have been proposed to study grapevine phenology in France. This has been mainly the result of the availability of the large databases described in the previous section. These studies have explored a set of very different issues, ranging from the modeling of some main processes of plant

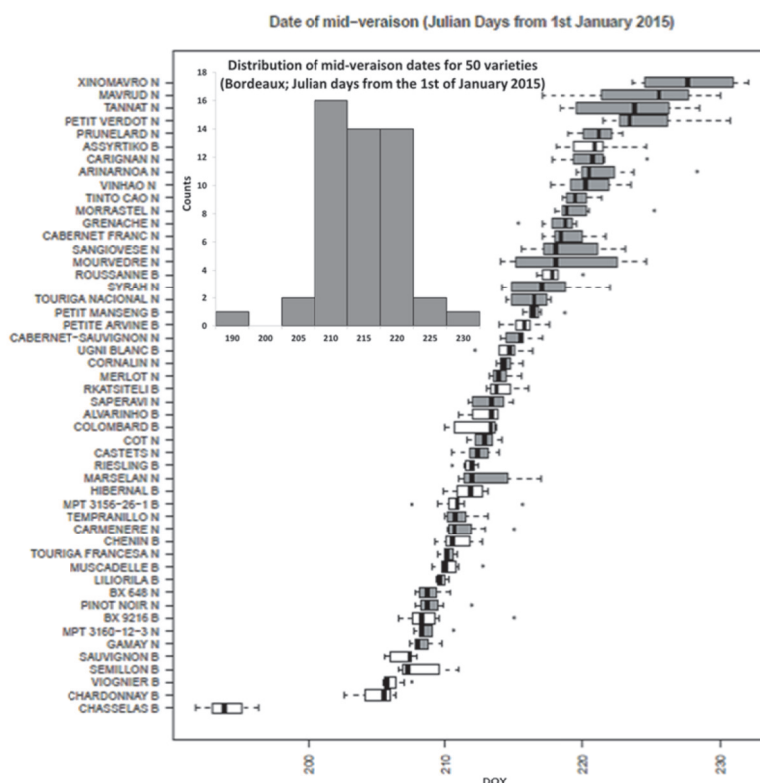
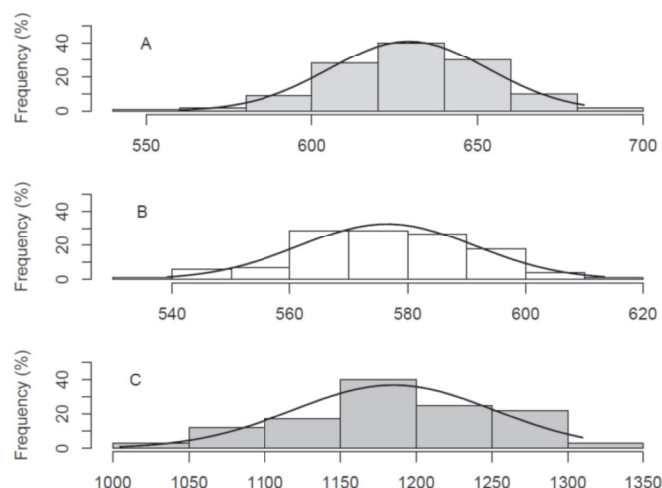


Figure 2. An example of variability among cultivars observed in the VITADAPT experiment (50 % veraison in the vintage 2015). DOY : Day Of the Year.





**Figure 3.** Histogram of segregations of the genotypic effects (heat sums in degree.days of maximum temperatures in 2008) in the Riesling x Gewürztraminer progeny. A) From 15 February to budbreak (base 2 °C); B) From budbreak to flowering (base 10 °C); C) From flowering to veraison (base 6 °C).

development (dormancy break and budbreak) to the classification of varieties for technical purposes, and most recently, the assessment of the impact of climate change on phenology of different varieties in various French vineyards.

Historically, investigations on the dormancy process of grapevines started in the 1960s with the work of Pouget. This author proposed a model to simulate budbreak for various varieties (Pouget, 1988) which was amended by Riou (1994). This model starts calculating the post-dormant phase after January 1st based on the assumption that the grapevine has already broken dormancy by that date (see Lavee and May, 1997 for a review). García de Cortázar-Atauri *et al.* (2009a) subsequently compared Pouget's amended model to the BRIN model, which takes into account the dormancy phase. The BRIN model was built using two different models: the Bidabe's model that was developed to simulate apple flowering (Bidabe, 1965a, b) and the Richardson model that was used to simulate peach flowering (Richardson *et al.*, 1974). The objective of this two-phase model was to determine if problems of dormancy could delay budbreak in some vineyards under future climate conditions, an issue that cannot be assessed with single-phase models.

Other main stages (flowering and veraison) have been simulated using the traditional model proposed by Amerine and Winkler (1944): the linear Growing Degree Days model (GDD) using daily mean temperatures, a base temperature of 10 °C and calculation starting on April 1st. This model has been widely used in the literature, and especially by García

de Cortázar-Atauri (2006) to simulate the impacts of climate change on grapevine using the STICS crop model. Subsequently, other models have been calibrated and tested successfully: the linear model proposed by Duchêne *et al.* (2010) using daily maximum temperatures as an input variable and different base temperatures according to the phases simulated; and the curvilinear model of Wang and Engel (1998) adapted by García de Cortázar-Atauri *et al.* (2010a) to simulate grapevine flowering and veraison for several varieties. While the Duchêne model is quite similar to the Winkler model, the Wang and Engel model incorporates several improvements to simulate phenology: the model identifies an optimal temperature for the species (values between 25-30 °C) and makes it possible to define a critical threshold temperature (in this case 40 °C) above which plant development stops completely.

Since 2008, Parker *et al.* (2011, 2013) have undertaken several studies in order to classify the largest number of grapevine varieties using a simple and robust model adapted at the species level (*Vitis vinifera* L.). The authors presented the GFV model (Grapevine Flowering and Veraison model), which is based on a linear function of the mean daily temperature using a base temperature of 0 °C and starting its calculation on March 1st. The model was calibrated from an important database containing more than 4000 observations for flowering and veraison for more than 100 varieties and from different sites, mostly in France, and a few sites in other countries (Switzerland and Italy). This model has been successfully tested in the VITADAPT field

experiment for the 2012-2015 period. The average absolute mean error for all the varieties (sum of mean error values by variety/number of varieties) was respectively 3.4 days for flowering and 4.4 days for veraison. This model is being tested also in other countries (i. e. New Zealand and Chile) with similar outcomes (Parker *et al.*, 2015b).

These models can be used to assess phenology evolution under different climate conditions (in space and time). Several studies have been conducted in recent years by using different models combined with climate change scenarios to quantify future changes in the phenology of different varieties in vineyards in France and abroad (e.g. García de Cortázar-Atauri, 2006, Duchêne *et al.*, 2010, García de Cortázar-Atauri *et al.*, 2010a, Pieri, 2010, Caffarra and Eccel, 2011, Cuccia *et al.*, 2014, Molitor *et al.*, 2014). All these studies showed that all main phenological stages (budbreak, flowering and veraison) will advance in the future, with greater advancements predicted in northern than in southern vineyards. In the CLIMATOR project, the authors calculated that flowering will advance by 8 days and veraison by 10 days for every degree increase in temperature in France (Gate and Brisson, 2010).

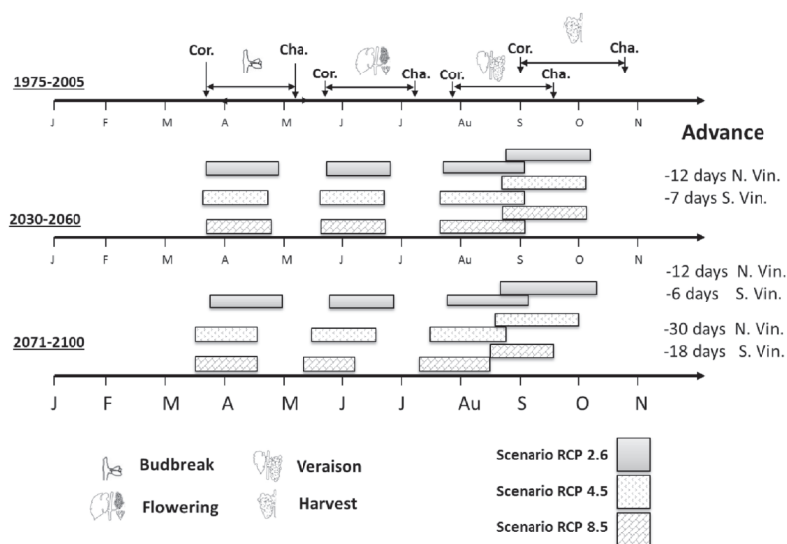
More recently in the LACCAVE project ([www6.inra.fr/laccave](http://www6.inra.fr/laccave)), García de Cortázar-Atauri *et al.* (2016) calculated phenology evolution for three varieties (Chardonnay, Syrah and Cabernet-

Sauvignon) across several vineyards in France. Figure 4 represents a synthesis of the results obtained.

These results indicated a change in the phenology (all stages) independently of the variety of approximately 6 to 12 days in 2050 regardless of the scenario and of 15 to 30 days depending on the variety, the scenario and the region in 2100 (Figure 4). For example, veraison could be 33 days earlier in Champagne using the scenario RCP 8.5, which generates the most significant changes. As a consequence of the calculated advances in phenology, the maturity phase is also calculated to advance to the warmest period of the year (July and August), generating important changes in the climatic conditions during grape ripening (Duchêne *et al.*, 2010). Finally, as shown in Figure 4, the time range for each phenological stage is calculated to compress under the different scenarios. The consequence for berry quality at harvest will have to be considered as well as the implications for future breeding programs.

### How can phenology be used as a key factor for adaptation?

As described above, phenology is a key factor for the adaptation of species to their environment (Chuine, 2010). In this context, it is also one of the factors that can be studied and modified (if possible) to evaluate



**Figure 4. Trends in budbreak, flowering, veraison and harvest (35 days after veraison) in French vineyards calculated for 3 different varieties: Chardonnay (early variety), Syrah (medium variety) and Cabernet-Sauvignon (late variety); using climate data from DRIAS (CNRM-Aladin model - [www.drias-climat.fr](http://www.drias-climat.fr)) for current/past climate conditions (black blocks – period 1975-2005) and three RCP scenarios: 2.6 (grey blocks), 4.5 (grey point blocks), 8.5 (grey brick blocks); for two different periods: 2030-2060 and 2071-2100.**

The length of the block represents the period for each phenological event for all the varieties collectively represented combined between the first appearance (50 %) in the first (Cor. = Corse) and the last vineyard (Cha. = Champagne).

N. Vin. represents northern vineyards. S. Vin. represents southern vineyards.

the adaptation capacity of a species/variety to the climatic conditions of a given location.

Unlike wild species (not-cultivated), the presence of a crop, or a variety, in a specific location is the result of a human choice. Historically, based on their experience and analysis of the environmental conditions (i. e. climate), growers have identified what species/varieties are best suited for production in each location. Thus, the best variety x location combinations need to be reconsidered in the context of climate change. One of the main considerations is to delay phenology with two potential options: changing the agricultural practices at the field/vineyard level or changing the variety used.

Recently, the ADVICLIM LIFE program showed that local variability of temperature (at the vineyard level) significantly affected the timing of phenological stages (Neethling *et al.*, 2016). This kind of results and analysis is very important in order to identify new potential areas to produce high quality wines and to define adaptation strategies to face future conditions (see also van Leeuwen and Destrac-Irvine, 2016). In the same way, Verdugo-Vásquez *et al.* (2016) characterized the variability of appearance of phenological stages at the plot level and highlighted the issues of managing these plots using simple models to simulate the phenological timing. This information can be used to better organize field work in order to optimize the choice of treatment dates, harvest date, etc.

At the plot level, several practices have been identified to delay phenology, in particular during the ripening period, in order to escape the summer heat. Very late pruning, after the end of winter and near the budbreak stage, can significantly delay budbreak. This technique is currently applied in northern vineyards in order to escape spring frost damages, but it may be also considered to delay the vegetative cycle of the vine (Branas, 1974, Friend and Trought, 2007). The leaf/fruit ratio has been also identified as a factor that can delay the start of the ripening phase and delay the time to reach a target sugar concentration (Parker *et al.*, 2014, 2015a). Rootstock choice has also been reported as a factor to delay the phenology of grafted varieties, having a significant impact for different stages (budbreak, veraison) of plant development (Tandonnet *et al.*, 2011, Bordenave *et al.*, 2014). Other techniques, not yet systematically used in France, have been developed to modify the timing of main phenological stages and maturity. These include: the use of growth regulators (application of retardants) to delay phenology (Böttcher *et al.*, 2011a, b), or growing grapes under

cover, which is usually used for table grapes and other fruit production, and which can advance or delay grapevine phenology according to different production objectives (Novello and De Palma, 2008).

As mentioned before, the other option to modify the phenology in a specific vineyard is based on the choice of the cultivar. In this context, several possibilities exist and are currently being explored in France. One of the simplest, when it is possible, is to change the current proportions of traditional varieties in some vineyards in order to promote late ripening cultivars. For example, in Bordeaux vineyards it may be an option to change the proportion of Merlot in favor of later varieties such as Cabernet-Sauvignon or Petit Verdot, all of which are current traditional varieties of the region. In other cases, particularly in northern vineyards, it may be possible to introduce late varieties that are not well suited so far due to their late maturity. This may also be true for southern vineyards, via the introduction of varieties from warmer and drier climates, for example Agiorgitiko from Greece and Touriga nacional from Portugal. Ancient cultivars abandoned for production, but still existing in the repositories, are currently being tested in some vineyards (for example Barbaroux and Mourvaison in Côteaux de Provence vineyards). In other vineyards where the cultivar choice is limited, as in Burgundy (only Pinot noir, Chardonnay, Aligoté and Gamay can be grown), the phenotypic clonal variability (for phenology and other characters) of the varieties currently grown is being analyzed in order to quantify the adaptive margin. As an example, clone 1209 of the cultivar Chenin has recently been integrated into the French catalog, because it is ripening 5-8 days later than the other Chenin clones (*Barbeau personal communication*).

While we have demonstrated above the importance of phenology, several authors have also shown that it is not possible to adapt to future conditions by taking into account only this parameter. Duchêne *et al.* (2010) showed in Alsace that this strategy was not sufficient to maintain the current climatic conditions during maturation in the future, even using a wide range of cultivars. This work, combined with that published by Parker *et al.* (2013), indicated that despite the numerous cultivars available in repositories, only a few cultivars may be late enough to escape the high temperatures expected to occur during ripening by the end of the century in France. In this context, breeders must also take into account this information and seek to incorporate other traits such as tolerance to high temperatures (heat shock resistance) and/or slower/low sugar accumulation rate in the berry. Nevertheless, the interest of



introducing new varieties will strongly depend on the situation in each single vineyard. It will be necessary to assess all the environmental and legal constraints (as for example for the vineyards being under the Protected Designation of Origin - PDO) and the capacity of each vineyard to produce high quality wines responding to consumer demand. In all cases, it is necessary to find a solution adapted to each vineyard, combining several options described above and taking into account the constraints and benefits of each vineyard.

## Conclusions

Phenology is a key factor in explaining the distribution and diversity of current vineyards in France. Through studying phenology, the impact of climate change on grapevine has been evaluated over recent decades. The knowledge and information obtained has also been used to assess potential phenology evolution in the future. All these findings have been achieved through the longstanding work of observation, analysis and compilation of this precious information by multiple organizations.

This article has presented a synopsis of research conducted to understand and model the main phenological stages (budbreak, flowering and veraison). However, even if those stages are important to understand the growth cycle of the plant, much remains to be investigated with respect to grape maturity, which is fundamental to determine berry composition at harvest. Some studies have already begun to model the berry maturation process (García de Cortázar-Atauri *et al.*, 2009b, Dai *et al.*, 2016). Nevertheless, it will also be important to produce simplified tools (such as the GFV model) for future analysis of the impact of climate change on this phase which is fundamental to define harvest composition.

Even if phenology is not the only trait to be considered for adapting grapevine to climate change, phenology plays a major role in the distribution of current cultivars. Several strategies have to be implemented in each vineyard to find the best solutions to adapt to future conditions, which may vary greatly depending on the scenario considered. It is therefore critical to continue to study phenology in order to better understand its ecophysiological (e.g. dormancy mechanism) and genetic (fundamental for breeding) attributes. To tackle these issues it is necessary to coordinate efforts on the observation (description of standard protocols, creation of new observatories, development of data management tools, maintenance and enhancement of cultivar and clone collections) via transverse and multidisciplinary

programs. Our capacity to adapt to climate change will depend on this multidisciplinary approach.

**Acknowledgements:** The authors would like to thank all observers, professionals or amateurs who have collected extensive data across France during many years for their efforts in the compilation of their phenological data. Without their work, this paper and many others would not have been possible. This work was supported by the LACCAGE and PERPHECLIM projects funded by the meta-program Adaptation of Agriculture and Forests to Climate Change (AAFCC) of the French National Institute for Agricultural Research (INRA).

## References

- Amerine, M.A., Winkler, A.J., 1944. Composition and quality of musts and wines of California grapes. University of California Berkeley.
- Bidabe, B., 1965a. Contrôle de l'époque de floraison du pommier par une nouvelle conception de l'action des températures. Comptes Rendus de l'Académie d'Agriculture de France 49, 934 – 945.
- Bidabe, B., 1965b. L'action des températures sur l'évolution des bourgeons de l'entrée en dormance à la floraison. Congr. Pom. (96 sess) Paris.
- Bordenave, L., Tandonnet, J.-P., Decroocq, S., Marguerit, E., Cookson, S.J., Esmenjaud, D., Ollat, N., 2014. Wild vitis as a germplasm resource for rootstocks. Exploitation of autochthonous and more used vines varieties - Oenoviti International Network I. Geisenheim, Germany.
- Böttcher, C., Boss, P.K., Davies, C., 2011a. Acyl substrate preferences of an IAA-amido synthetase account for variations in grape (*Vitis vinifera* L.) berry ripening caused by different auxinic compounds indicating the importance of auxin conjugation in plant development. Journal of Experimental Botany 62, 4267 – 4280.
- Böttcher, C., Harvey, K., Forde, C.G., Boss, P.K., Davies, C., 2011b. Auxin treatment of pre-veraison grape (*Vitis vinifera* L.) berries both delays ripening and increases the synchronicity of sugar accumulation. Australian Journal of Grape and Wine Research 17, 1 – 8.
- Boursiquot, J.-M., Dessup, M., Rennes, C., 1995. Distribution of the main phenological, agronomical and technological characters of *Vitis vinifera* L. Vitis 34, 31 – 35.
- Branas, J., 1974. Viticulture. Ed. Dehan. 990 pp
- Caffarra, A., Eccel, E., 2011. Projecting the impacts of climate change on the phenology of grapevine in a mountain area. Australian Journal of Grape and Wine Research 17, 52 – 61.
- Chuine, I., 2010. Why does phenology drive species distribution? Philosophical Transactions of the Royal Society B: Biological Sciences 365, 3149 – 3160.

- Chuine, I., Yiou, P., Viovy, N., Seguin, B., Daux, V., Le Roy Ladurie, E., 2004. Historical phenology: grape ripening as a past climate indicator. *Nature* 432, 289 – 290.
- Chuine, I., García de Cortázar-Atauri, I., Kramer, K., Hänninen, H., 2013. Plant development models, in: *Phenology: An Integrative Environmental Science*. Springer, pp. 275 – 293.
- Cook, B.I., Wolkovich, E.M., 2016. Climate change decouples drought from early wine grape harvests in France. *Nature Climate Change* 6, 715 – 719.
- Coombe, B.G., 1995. Growth stages of the grapevine: adoption of a system for identifying grapevine growth stages. *Australian Journal of Grape and Wine Research* 1, 104 – 110.
- Cuccia, C., Bois, B., Richard, Y., Parker, A.K., García de Cortázar-Atauri, I., van Leeuwen, C., Castel, T., 2014. Phenological model performance to warmer conditions: application to pinot noir in Burgundy. *Journal International des Sciences de la Vigne et du Vin* 48, 169 – 178.
- Dai, Z., Wu, H., Baldazzi, V., van Leeuwen, C., Bertin, N., Gautier, H., Wu, B., Duchêne, E., Gomès, E., Delrot, S., Lescouret, F., Génard, M., 2016. Inter-species comparative analysis of components of soluble sugar concentration in fleshy fruits. *Frontiers in Plant Science* 7, 649.
- Daux, V., García de Cortázar-Atauri, I., Yiou, P., Chuine, I., Garnier, E., Le Roy Ladurie, E., Mestre, O., Tardaguila, J., 2012. An open-access database of grape harvest dates for climate research: data description and quality assessment. *Climate of the Past* 8, 1403 – 1418.
- Domergue, M., García de Cortázar-Atauri, I., Seguin, B., Brisson, N., Ripoche, D., 2003. Le réchauffement récent du climat en France et ses conséquences pour l'agriculture, in: Blazejczyk, K., Adamczyk, A.B., Polska Akademia Nauk-Instytut Geografii i Przestrzennego, Z. (Eds.), 16. Colloque de l'Association Internationale de Climatologie, Dokumentacja Geograficzna. Polska Akademia Nauk, Warszawa (POL) Varsovie (POL), pp. 85 – 88.
- Duchêne, E., Schneider, C., 2005. Grapevine and climatic changes: a glance at the situation in Alsace. *Agronomy for Sustainable Development* 25, 93 – 99.
- Duchêne, E., Huard, F., Dumas, V., Schneider, C., Merdinoglu, D., 2010. The challenge of adapting grapevine varieties to climate change. *Climate Research* 41, 193 – 204.
- Duchêne, E., Butterlin, G., Dumas, V., Merdinoglu, D., 2012. Towards the adaptation of grapevine varieties to climate change: QTLs and candidate genes for developmental stages. *Theoretical and Applied Genetics* 124, 623 – 635.
- Etien, N., Daux, V., Masson-Delmotte, V., Stievenard, M., Bernard, V., Durost, S., Guillemin, M.T., Mestre, O., Pierre, M., 2008. A bi-proxy reconstruction of Fontainebleau (France) growing season temperature from AD 1596 to 2000. *Climate of the Past* 4, 91 – 106.
- Etien, N., Daux, V., Masson-Delmotte, V., Mestre, O., Stievenard, M., Guillemin, M., Boettger, T., Breda, N., Haupt, M., Perraud, P., 2009. Summer maximum temperature in northern France over the past century: instrumental data versus multiple proxies (tree-ring isotopes, grape harvest dates and forest fires). *Climatic Change* 94, 429 – 456.
- Fechter, I., Hausmann, L., Zyprian, E., Daum, M., Holtgräwe, D., Weisshaar, B., Töpfer, R., 2014. QTL analysis of flowering time and ripening traits suggests an impact of a genomic region on linkage group 1 in *Vitis*. *Theoretical and Applied Genetics* 127, 1857 – 1872.
- FranceAgriMer - Observatoire de la viticulture française, 2015. Surface par cépage - 2014.
- Friend, A.P., Trought, M.C., 2007. Delayed winter spur-pruning in New Zealand can alter yield components of Merlot grapevines. *Australian Journal of Grape and Wine Research* 13, 157 – 164.
- García de Cortázar-Atauri, I., 2006. Adaptation du modèle STICS à la vigne (*Vitis vinifera* L.). Utilisation dans le cadre d'une étude d'impact du changement climatique à l'échelle de la France. Thèse de doctorat, Ecole Supérieure Nationale d'Agronomie de Montpellier.
- García de Cortázar-Atauri, I., Brisson, N., Gaudillere, J.-P., 2009a. Performance of several models for predicting budburst date of grapevine (*Vitis vinifera* L.). *International Journal of Biometeorology* 53, 317 – 326.
- García de Cortázar-Atauri, I., Brisson, N., Ollat, N., Jacquet, O., Payan, J.-C., 2009b. Asynchronous dynamics of grapevine (*Vitis vinifera*) maturation: experimental study for a modelling approach. *Journal International des Sciences de la Vigne et du Vin* 43, 83 – 97.
- García de Cortázar-Atauri, I., Chuine, I., Donatelli, M., Parker, A., van Leeuwen, C., 2010a. A curvilinear process-based phenological model to study impacts of climatic change on grapevine (*Vitis vinifera* L.). *Proceedings of Agro 2010: the 11th ESA Congress*, Montpellier, France (Agropolis International Editions: Montpellier), pp 907 – 908.
- García de Cortázar-Atauri, I., Daux, V., Garnier, E., Yiou, P., Viovy, N., Seguin, B., Boursiquot, J.-M., Parker, A.K., Van Leeuwen, C., Chuine, I., 2010b. Climate reconstructions from grape harvest dates: methodology and uncertainties. *The Holocene* 20, 599 – 608.

- García de Cortázar-Atauri, I., Duchêne, E., Destrac-Irvine, A., Barbeau, G., de Rességuier, L., Lacombe, T., Parker, A.K., Saurin, N., van Leeuwen, C., 2016. Assessment of future climatic conditions in French vineyards. Consequences for defining adaptation strategies. Climwine, sustainable grape and wine production in the context of climate change, 11-13 April 2016, Bordeaux.
- Gate, P., Brisson, N., 2010. Advancement of phenological stages and shortening of phases. Climate change, agriculture and forests in France: simulations of the impacts on the main species. The Green Book of the CLIMATOR project (2007 – 2010). ADEME, Angers, France, pp. 65 – 78.
- Grzeskowiak, L., Costantini, L., Lorenzi, S., Grando, M.S., 2013. Candidate loci for phenology and fruitfulness contributing to the phenotypic variability observed in grapevine. Theoretical and Applied Genetics 126, 2763 – 2776.
- Jones, G.V., 2013. Winegrape phenology, in: Phenology: An Integrative Environmental Science. Springer, pp. 563 – 584.
- Jones, G.V., Duchene, E., Tomasi, D., Yuste, J., Braslavská, O., Schultz, H., Martinez, C., Boso, S., Langellier, F., Perruchot, C., 2005. Changes in European winegrape phenology and relationships with climate, in: XIV International GESCO Viticulture Congress, Geisenheim, Germany, 23-27 August, 2005, pp. 54 – 61.
- Lacombe, T., Boursiquot, J.-M., Laucou, V., Di Vecchi-Staraz, M., Péros, J.-P., This, P., 2013. Large-scale parentage analysis in an extended set of grapevine cultivars (*Vitis vinifera* L.). Theoretical and Applied Genetics 126, 401 – 414.
- Lavee, S., May, P., 1997. Dormancy of grapevine buds - Facts and speculation. Australian Journal of Grape and Wine Research 3, 31 – 46.
- Legave, J.-M., Blanke, M., Christen, D., Giovannini, D., Mathieu, V., Oger, R., 2013. A comprehensive overview of the spatial and temporal variability of apple bud dormancy release and blooming phenology in Western Europe. International Journal of Biometeorology 57, 317 – 331.
- Meier, N., Rutishauser, T., Pfister, C., Wanner, H., Luterbacher, J., 2007. Grape harvest dates as a proxy for Swiss April to August temperature reconstructions back to AD 1480. Geophysical Research Letters 34, L20705, doi:10.1029/2007GL031381.
- Menzel, A., 2005. A 500 year pheno-climatological view on the 2003 heatwave in Europe assessed by grape harvest dates. Meteorologische Zeitschrift 14, 75 – 77.
- Menzel, A., Sparks, T.H., Estrella, N., Koch, E., Aasa, A., Ahas, R., Alm-Kübler, K., Bissolli, P., Braslavská, O., Briede, A., Chmielewski, F.M., Crepinsek, Z., Curnel, Y., Dahl, Å., Defila, C., Donnelly, A., Filella, Y., Jatzczak, K., Måge, F., Mestre, A., Nordli, Ø., Peñuelas, J., Pirinen, P., Remišová, V., Scheifinger, H., Striz, M., Susnik, A., Van Vliet, A.J.H., Wielgolaski, F.-E., Zach, S., Züst, A., 2006. European phenological response to climate change matches the warming pattern. Global Change Biology 12, 1969 – 1976.
- Molitor, D., Caffarra, A., Sinigoj, P., Pertot, I., Hoffmann, L., Junk, J., 2014. Late frost damage risk for viticulture under future climate conditions: a case study for the Luxembourgish winegrowing region. Australian Journal of Grape and Wine Research 20, 160 – 168.
- Neethling, E., Barbeau, G., Julien, S., Le Roux, R., Quénot, H., 2016. Local-based approach for assessing climate change adaptation in viticulture. Climwine, sustainable grape and wine production in the context of climate change, 11-13 April 2016, Bordeaux.
- Novello, V., De Palma, L., 2008. Growing grapes under cover. Acta Horticulturae 785, 353 – 362.
- Parker, A.K., García de Cortázar-Atauri, I., van Leeuwen, C., Chuine, I., 2011. General phenological model to characterise the timing of flowering and veraison of *Vitis vinifera* L. Australian Journal of Grape and Wine Research 17, 206 – 216.
- Parker, A., García de Cortázar-Atauri, I., Chuine, I., Barbeau, G., Bois, B., Boursiquot, J.-M., Cahurel, J.-Y., Claverie, M., Dufourcq, T., Gény, L., Guimberteau, G., Hofmann, R.W., Jacquet, O., Lacombe, T., Monamy, C., Ojeda, H., Panigai, L., Payan, J.-C., Rodriguez Lovelle, B., Rouchaud, E., Schneider, C., Spring, J.-L., Storchi, P., Tomasi, D., Trambouze, W., Trought, M., van Leeuwen, C., 2013. Classification of varieties for their timing of flowering and veraison using a modelling approach: a case study for the grapevine species *Vitis vinifera* L. Agricultural and Forest Meteorology 180, 249 – 264.
- Parker, A.K., Hofmann, R.W., van Leeuwen, C., McLachlan, A.R.G., Trought, M.C.T., 2014. Leaf area to fruit mass ratio determines the time of veraison in Sauvignon Blanc and Pinot Noir grapevines. Australian Journal of Grape and Wine Research 20, 422 – 431.
- Parker, A.K., Hofmann, R.W., van Leeuwen, C., McLachlan, A.R.G., Trought, M.C.T., 2015a. Manipulating the leaf area to fruit mass ratio alters the synchrony of total soluble solids accumulation and titratable acidity of grape berries. Australian Journal of Grape and Wine Research 21, 266 – 276.
- Parker, A., Schulmann, T., Sturman, A., Agnew, R., Zavar-Reza, P., Katurji, M., Gendig, E., Trought, M.C.T. 2015b. Understanding flowering of Sauvignon blanc in the Marlborough region, New Zealand, using high-resolution weather forecasting and the grapevine flowering veraison model, in: 19th

- International Symposium of the Group of International Experts of Vitivinicultural Systems for Co-Operation (GIESCO), Gruissan, France, pp. 271 – 276.
- Pieri, P., 2010. Climate change and grapevines: main impacts. Climate change, agriculture and forests in France: simulations of the impacts on the main species. The Green Book of the CLIMATOR project (2007 – 2010). ADEME, Angers, France, pp. 213 – 223.
- Pouget, R., 1988. Le débourrement des bourgeons de la vigne: méthode de prévision et principes d'établissement d'une échelle de précocité de débourrement. *Connaissance de la Vigne et du Vin* 22, 105 – 123.
- Richard, Y., Castel, T., Bois, B., Cuccia, C., Marteau, R., Rossi, A., Thévenin, D., Toussaint, H., 2014. Évolution des températures observées en Bourgogne (1961-2011). *Bourgogne Nature* 19, 110 – 117.
- Richardson, E.A., Seeley, S.D., Walker, D.R., 1974. A model for estimating the completion of rest for "Redhaven" and "Elberta" peach trees. *HortScience* 9, 331 – 332.
- Riou, C., 1994. The effect of climate on grape ripening: application to the zoning of sugar content in the European community. Office des Publications Officielles des Communautés Européennes, Luxembourg. 322 pp
- Schwartz, M.D., 2013. Phenology: An Integrative Environmental Science. Springer Netherlands, Dordrecht. 610 pp
- Steinbach, D., Alaux, M., Amselem, J., Choisne, N., Durand, S., Flores, R., Keliet, A.-O., Kimmel, E., Lapalu, N., Luyten, I., Michotey, C., Mohellibi, N., Pommier, C., Reboux, S., Valdenaire, D., Verdelet, D., Quesneville, H., 2013. GnpIS: an information system to integrate genetic and genomic data from plants and fungi. *Database: The Journal of Biological Databases and Curation* 2013, bat058, doi:10.1093/database/bat058.
- Tandonnet, J.-P., Bordenave, L., Decroocq, S., Ollat, N., 2011. Etude de la variabilité génétique au sein du genre *Vitis* pour le caractère de vigueur conférée par le porte-greffe. In: Darriet P, ed. IXth international symposium of Enology. Bordeaux: Dunod, 180-186.
- van Leeuwen, C., Darriet, P., 2016. The impact of climate change on viticulture and wine quality. *Journal of Wine Economics* 11, 150 – 167.
- van Leeuwen, C., Destrac-Irvine, A., 2016. Modified grape composition under climate change conditions requires adaptations in the vineyard. *Climwine*, sustainable grape and wine production in the context of climate change, 11-13 April 2016, Bordeaux.
- Verdugo-Vásquez, N., Acevedo-Opazo, C., Valdés-Gómez, H., Araya-Alman, M., Ingram, B., García de Cortázar-Atauri, I., Tisseyre, B., 2016. Spatial variability of phenology in two irrigated grapevine cultivar growing under semi-arid conditions. *Precision Agriculture* 17, 218 – 245.
- Wang, E., Engel, T., 1998. Simulation of phenological development of wheat crops. *Agricultural Systems* 58, 1 – 24.
- Yiou, P., García de Cortázar-Atauri, I., Chuine, I., Daux, V., Garnier, E., Viovy, N., van Leeuwen, C., Parker, A.K., Boursiquot, J.-M., 2012. Continental atmospheric circulation over Europe during the Little Ice Age inferred from grape harvest dates. *Climate of the Past* 8, 577 – 588.