EIP-AGRI Focus Group

Protecting fruit production from frost damage

MINIPAPER 5: Phenology and critical temperatures

January 2019

Authors

Carlos Miranda (Coord.), Alois Bilavcik, Roman Chaloupka, Sabrina Dreisiebner-Lanz, Maciej Gąstoł, Eike Luedeling, Susan McCallum

funded by European Commission

Introduction

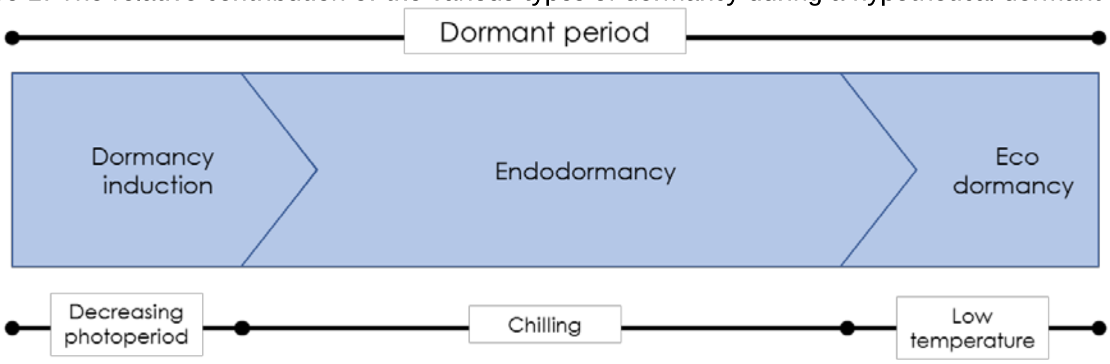
The aim of this minipaper is to present and discuss available knowledge on frost damage critical temperatures and phenological event simulation, that are fundamental for frost damage prediction models. We start with an overview of the physiological background of plants related with dormancy process.
The degree of frost damage depends on weather conditions as well as on the stage of the plant. As the phenological stage is crucial for the susceptibility to frost, it is important to understand the physiology of the plant and the influencing factors for budbreak or bloom. In addition to the plant stage, the critical temperature for the plant depends on various factors, which – to some extent – can be influenced by the farmer. In order to predict the risk of frost in time, phenological models can be helpful to predict plant development.

Physiology of budbreak and bloom

Perennial woody fruit species cultivated in temperate zones synchronize their annual growth patterns with seasonal environmental changes. During unfavourable winter conditions, temperate fruit species use bud dormancy as a defensive mechanism. Bud dormancy is classified in two stages (Figure 1):

- **Endodormancy**: Buds are latent due to internal factors, and even under favourable environmental conditions they are unable to grow. Dormant buds will not grow until certain biochemical changes occur. Accumulation of chilling promote the changes that break dormancy of buds.
- **Ecodormancy**: After chilling is completed the plants are dormant only because of environmental factors (cold or cool weather, day length) are preventing growth. Buds can be induced to break by exposure to a specific 'amount' of heat. Evidence suggest that chilling and heat needs are not entirely fixed, but can partially compensate for each other, but the exact nature of this compensation is poorly understood.

Figure 1: The relative contribution of the various types of dormancy during a hypothetical dormant period[1].



Evergreen plants, such as Citrus trees, do not have a stable or pronounced dormancy, but growth is slowed down during winter and plants can reach a phase of about three months of semi-dormancy, induced by lower temperatures. Some citrus are able to flower all year long, but the majority of flowers is produced in the months of February/March on the northern hemisphere. In tropical climates, no dormancy is induced because of the lack of lower temperatures. Drought stress can instead provoke a kind of dormancy and increase therefore cold hardiness. However, due to the possible damage caused by drought stress, the withholding of irrigation water does not seem feasible in this context.

Critical temperatures

Factors influencing the susceptibility to frost

Knowledge on critical temperatures of buds according to literature may, together with local weather forecasts, give information on frost damage risks for use to manage active frost protection methods. The temperature at which fruit buds are injured depends primarily on their stage of development. As they begin to

[1] Lang, GA, Early JD, Arroyave NJ, Darnell RL, Martin GC, Stutte, GW. 1985. Dormancy: Toward a reduced, universal terminology. HortScience 20: 809-912.

funded by European Commission

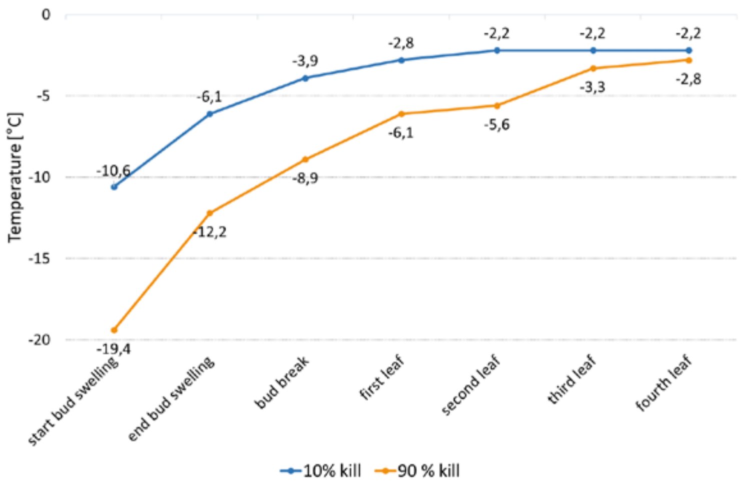
swell and expand into blossoms, their water content quickly rises and become therefore less resistant to freeze injury. Therefore, critical temperatures increase as the season progresses. Moreover, the temperature that produces 90% bud kill increases more rapidly and approaches the temperature that produces 10% bud kill, to the point that in some species, like cherry, the temperature differential for 10% and 90% damage is negligible during flowering.

Resistance to freeze injury varies within trees as it does among species, cultivars, and even within the tree itself (partially explained by orientation and height inside the tree). However, apparently similar flowers, in the same developmental stage and in similar position often present differences in cold resistance and while some of them are killed under a spring frost, others can continue their development. Flower bud development is a continuous process associated with a progressive vulnerability of the pistil to low temperatures, and pistil development is not strictly linked with changes in the external flower appearance. For this reason, even apparently similar flowers in the same phenological stage and in a similar position on the tree often present differences in cold resistance. Likewise, cold hardiness of flower buds has been related to their nutritive status and the conditions that deplete the pool of assimilates in the tissues. That may explain the effect that stress factors like previous crop load, pests and diseases or droughts, have on bud hardiness and be responsible for some of the orchard to orchard differences often recorded. Regarding nutrients, especially the nitrogen and potassium supply plays an important role in frost hardiness. Not only lack, but in case of nitrogen also oversupply can induce higher susceptibility to spring frost. Moreover, resistance to freeze among buds of different cultivars of the same species may be even higher than among different species. Some studies have found up to 2ºC difference between the least and the most frost hardy cultivar on a same species. Frost damage sensitivity at the same temperature and phenological stage is also dependent on previous weather conditions, orchard topography, and the characteristics of the frost night, such us humidity, rate of temperature decrease and increase (quick changes are more damaging), and the duration of low temperatures.

Grapevine[2]

Frost tolerance of grapevine buds and wood during dormancy is rather good, and the grapevines are (to a certain extent) capable of switching between de-hardening and hardening processes, depending on environmental conditions. With the start of bud swelling, the resistance to low temperatures and hardening capability decreases rapidly (Figure 2). Green shoots of grapevine have a high content of water and are therefore prone to frost damages. Minus temperatures of -2/-3°C can already lead to sustainable damages in plant tissues.

Figure 2. Critical temperatures for 10% and 90% bud kill in grapevine[3]



[2] Keller, Markus (2017): Ein Fall der inneren und äußeren Sicherheit. Der Winzer 03/2017

[3] Richard L. Snyder und J. Paulo De Melo-Abreu, „Frost protection: fundamentals, practice, and economics - Volume 1“, 2005, http://www.fao.org/docrep/008/y7223e/y7223e0c.htm#bm12.15.

Stonefruit / Pomefruit

The dormant buds of apple trees can withstand low temperatures down to -30°C, but at full bloom, the blossoms are very frost susceptible and freeze with temperatures close to zero. An example of the spring shift of the frost resistance of apple flower buds, related to the freezing events in the flower primordia, is displayed in Table 1. Pear frost sensitivity is considered similar to that of apples, although with slight variations depending on the phenological stage. There are also some differences between varieties, usually small ones (less than 1ºC or 2ºC). There are numerous studies in this sense, although with contradictory results in some cases, due to the action of other factors, as well as possible differences in the state of the material. To give some examples, Golden, Jonathan and Reinette du Canada are considered more susceptible than Red Delicious or Cox' Orange. In pear, Williams, Comice and Beurre Hardy are more susceptible than Conference, Guyot or Beurre Bosc.

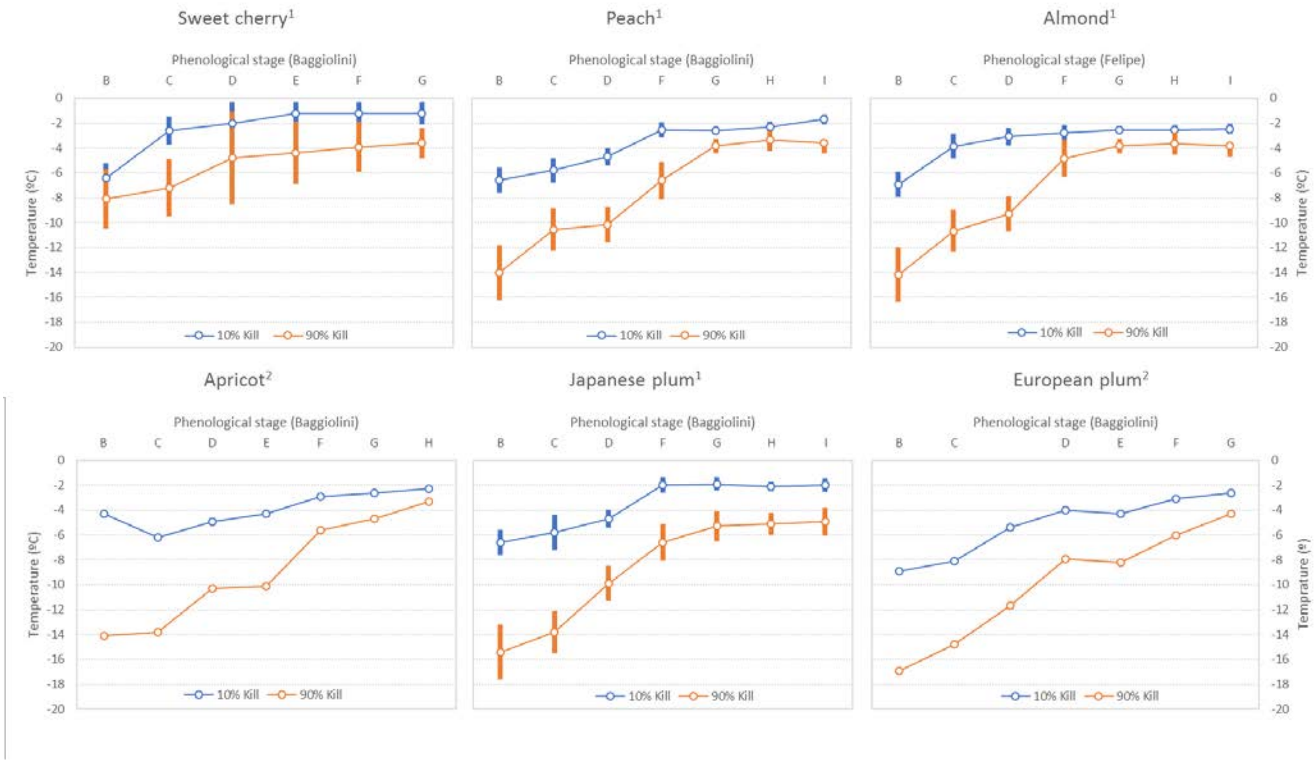
Table 1: Freezing of parts of flower apple shoots in different phenological phases.

	Half-inch green /tight cluster	Tight cluster	Green cluster	Bloom
Twig ice formation (°C)	-3.2	-4.3	-2.5	-3.6
Flower ice formation (°C)	-12.5	-11.8	-9.7	-4.3
Difference (°C)	*7.8*	*7.4*	*5.0*	*0.7*

A similar shift in spring frost resistance can be observed in stone fruit species, but with higher differences between species. An example of this is shown in Figure 3, in which buds of several species were subjected to frost tests under standardized conditions to compare the differences between species in the same phenological stage. In the Figure it can be observed that the range of temperatures at which a certain damage level can be expected is usually quite broad, as there are many factors still unknown or difficult to control which influence bud frost hardiness. Cherry is much more sensitive, even at bud swell and budbreak, followed by almond, for which the difference between 10% and 90% bud kill is <1.5 ºC at postbloom stages. At prebloom stages, Japanese plums appear to be less hardy than European plums, but from bloom onwards, their resistance appears to be quite similar. Peach has a similar hardiness to Japanese plums at prebloom and bloom stages and is less hardy at postbloom. In short, between bud swelling (B) to jacket split (I) stages, the order of the stone species from the least to the most frost resistant is sweet cherry, almond, peach, apricot, Japanese plum and European plum. The differences, although significant, range usually within a few tenths of degree, and differences in frost resistance between varieties of the same species can be even higher than between species.

funded by European Commission

Figure 3. Critical temperature (ºC) values for several stone fruit species, killing 10% and 90% of buds. When present, bars indicate the range of temperatures at which the damage level can be expected



Sources:

1: Miranda C, et al. 2005. Variability in the relationship between frost temperature and injury level for some cultivated Prunus species. Hortscience 40:357-361, http://hortsci.ashspublications.org/content/40/2/357.full.pdf

2. Snyder R.L. and De Melo-Abreu J.P. 2005 Frost protection: fundamentals, practice, and economics - Volume 1“, 2005, http://www.fao.org/docrep/008/y7223e/y7223e0c.htm#bm12.15.

Citrus[4,5]

The attained degree of dormancy influences the susceptibility to freezing: dormant trees will be less damaged than trees that are actively growing. The presence of fruits on the trees maintains trees in active condition and therefore prevents the development of dormancy. Cold hardiness to winter frost also depends on the species; temperatures between approximately -7 (i.e. Kumquats) and -1,7 °C (i.e. limes) can be withstood without leaf or wood damage, assuming trees are established and hardened.

However, spring frosts generally cause more damage than winter frosts. Blossom and young fruits of all citrus varieties are very tender and temperatures of -1/-0,5°C already for a short time are lethal. Fruits are usually damaged at similar – under some conditions also higher – temperature as leaves. Susceptibility of citrus fruits depends on the ripening degree of fruits, as shown in Table 2.

4 The Citrus Industry. Herbert John Webber, Leon Dexter Batchelor

5 Cold Hardiness in citrus as related to dormancy. William C. Cooper. https://fshs.org/proceedings-o/1959-vol-72/61-66%20(COOPER).pdf

Table 2: Critical temperature when citrus fruits, buds or blossoms begin to freeze[6]

Citrus species	Critical temperature [°C]
Green oranges	-1,9 to -1,4
Half ripe oranges, grapefruits and mandarins	-2,2 to -1,7
Ripe oranges, grapefruit and mandarins	-2,8 to -2,2
Button lemons	-1,4 to -0,8
Tree ripe lemons	-1,4 to -0,8
Green lemons (diameter >12mm)	-1,9 to -1,4
Lemon buds and blossoms	-2,8

Soft fruit

Freezing temperatures can have a devastating effect on soft fruit and tree crop production, if they occur during critical developmental periods (Table 3).

Table 3. Critical temperatures for strawberries and blueberries

Strawberries	Critical temp· ºC	Blueberries	Critical temp. ºC
Tight bud	-2	Early pink bud	-5 to -4
Open blossom	-5	Late pink bud	-4 to -3
Green fruit	-1	Full bloom	-4 to -2
Petal fall	-2	Petal fall	-2
Flower and fruit	-1	Expanded fruit	-2

Available phenological models

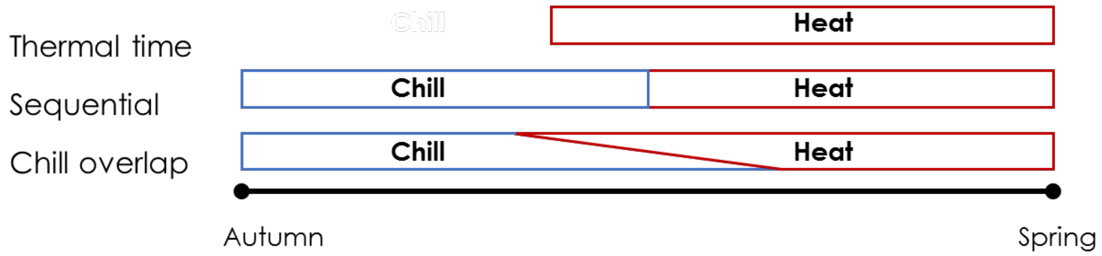
Types of models

Phenological models are used as a tool to predict the phenology of fruit species and assume that temperature is the main factor regulating bud development. Over the years, several conceptual approaches have been developed, which vary on how they manage the interplaying between chilling (temperatures breaking dormancy) and heat (temperatures forcing growth after dormancy release). Three types of models, depending on the conceptual approach used, are commonly used (Figure 4):

- **Thermal time**: The simplest ones, consider that only heat accumulated from a set date to a given sum explain the date of occurrence of the phenological stage (i.e, it assumes that dormancy release occurs before that date).
- **Sequential model**: Consider that chilling and heat have independent effects. They consist of an accumulation of chill up to the plant requirement followed by heat up to forcing requirement, with no overlap between both phases.
- **Alternating (or chill overlap):** Consider chill and heat and include a partially compensatory relationship between chill and forcing heat accumulation, by which some chill beyond a minimum requirement can reduce the amount of heat necessary.

6 Snyder R.L. and De Melo-Abreu J.P. 2005 Frost protection: fundamentals, practice, and economics - Volume 1", 2005, http://www.fao.org/docrep/008/y7223e/y7223e0c.htm#bm12.15.

Figure 4. Conceptual approaches for the main types of phenological models used in fruit species

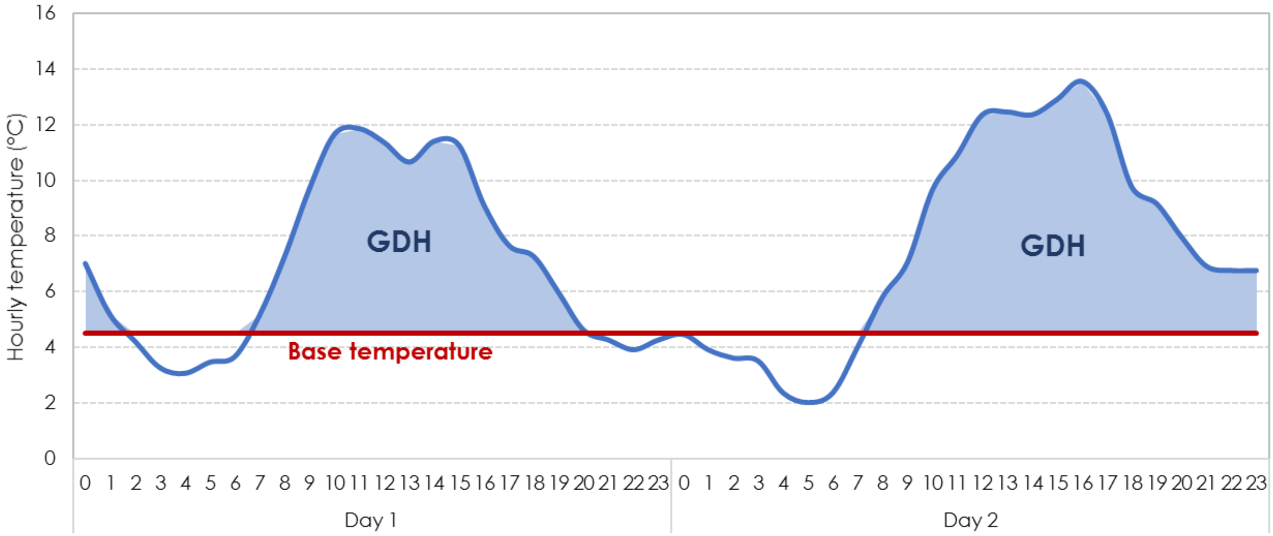


In most fruit species, the Thermal model is inappropriate because it assumes that the chill requirement is met every year. Most studies that have tested the performance of sequential models have found that some combinations are able to predict bloom dates to within a few days (< 1 week or better) of actual bloom dates. However, these models are ill-suited for Mediterranean or warm climates, with mild winters, or for a changing climate of warming winters. Sequential models do not include the partially compensatory relationship between chill and heat accumulation and, as such, they reflect just frequent combinations of chill and heat, not the bare minimum necessary for bloom. For that reason, in recent years a growing interest in alternating methods able to compensate chill and heat has been demonstrated.

Models also differ in how they calculate chill and heat. Heat is calculated as the accumulation of growing degrees (GD), defined as number of temperature degrees above a certain threshold base temperature (T_b), which varies between species or cultivars. The base temperature is the temperature below which bud growth is zero. GDs are calculated using daily (growing degree days, GDD) or hourly temperature (growing degree hours, GDH):

- **GDD**: by subtracting T_b from the average daily temperature for each day, and then accumulating the degree-days. If the average daily temperature is below T_b, GDD=0 for that day.
- **GDH**: by subtracting T_b from the hourly temperature (Figure 5) and then accumulating the degree-hours (Figure 4). If the hourly temperature is below T_b, GDH=0 for that hour.

Figure 5. Example of growing degree hours accumulated in two consecutive days for a base temperature of 4.5°C.

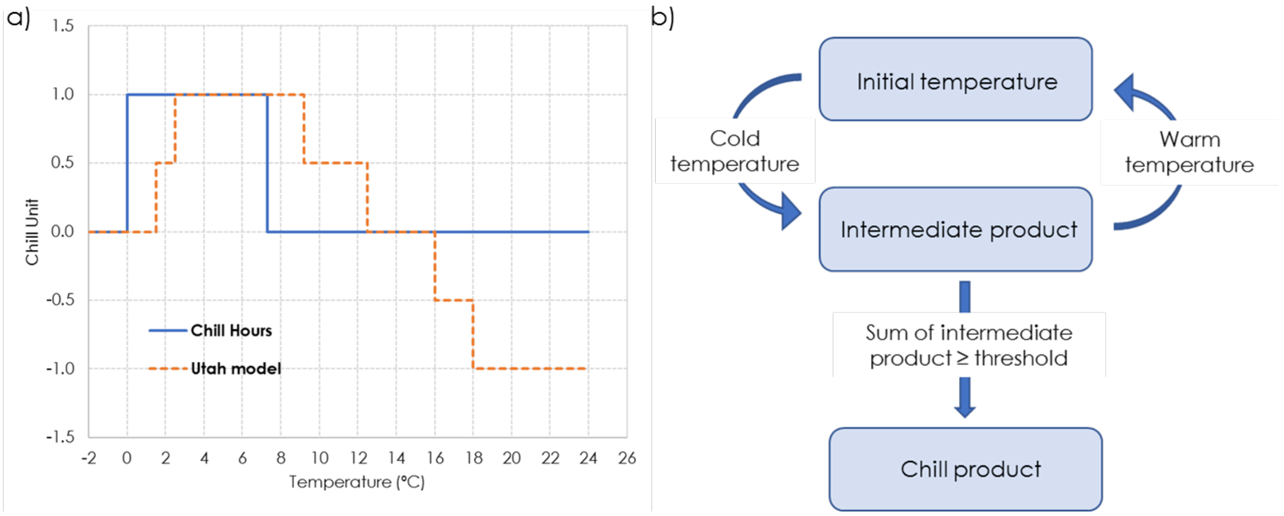


Chill accumulation of fruit trees has been simulated using many models, but three are the most commonly found in literature. All of them require hourly temperatures:

- **Chill hours (Weinberger or 0-7.2 °C model)**: Sums chill hours over winter, with one chill hour accumulated for hourly temperatures between 0 and 7.2°C.
- **Utah model:** This model is characterized by differential weighting of temperature ranges (Figure 6a), including negative weights for temperatures above 15.9°C. This model recognizes that different temperatures vary in effectiveness in accumulating chill as well as a negative influence of high temperatures on previously accumulated chill. Variations of the Utah model have been developed for different regions and fruit crops.
- **Dynamic model:** This model considers chill accumulation more interactively, incorporating a two-step process to represent chill accumulation, which makes it the most plausible among the common models. In a similar way to the Utah model, optimum chilling temperatures and negation aspects of high temperatures are incorporated. However, these features only influence the production of an intermediate product (Figure 6b). Once a certain amount of this intermediate product is amassed, it is banked as a chill portion that cannot be altered by subsequent temperature conditions. This model also includes the positive influence of moderate temperatures on chill accumulation.

funded by European Commission

Figure 6. Representation of the key aspects in chill models. a) Chill allocation for a given temperature for the Chill hours and Utah models (units are not comparable). b) Schematic of the Dynamic model. Source: *Adapted from Darbyshire et al (2011)*[7]



Users of chill models have often been tempted to adopt the simplest model – Chilling Hours – but it is important to note that model choice can have a strong influence on how temperate dynamics are interpreted (Figure 7).

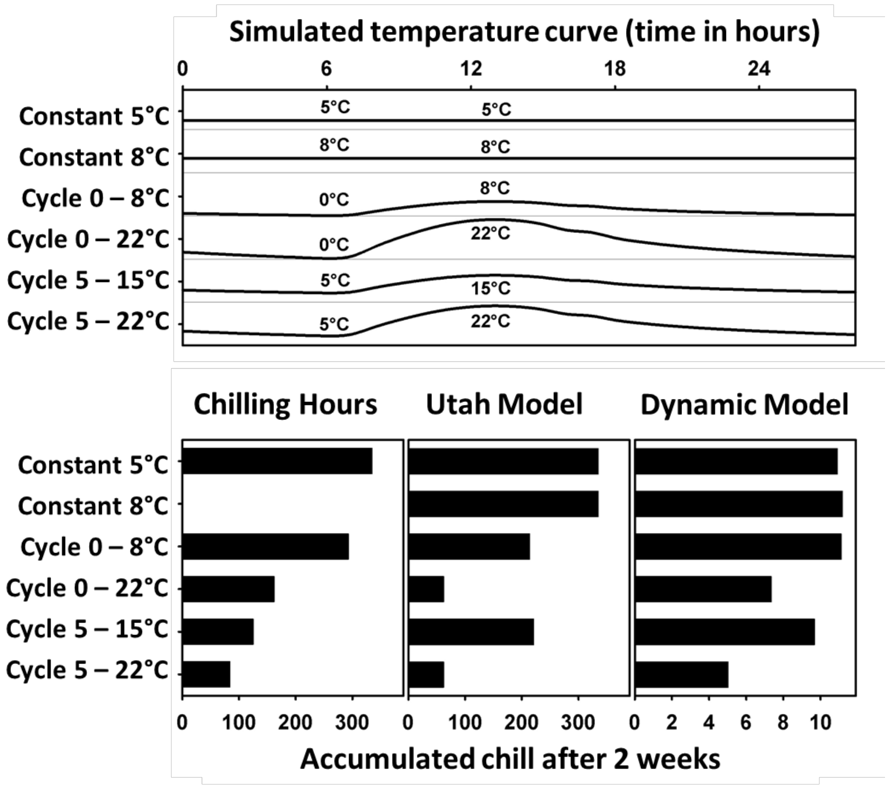


Figure 7. Chill computed with the three most commonly chill models for six simulated temperature curves. Note that the Utah Model and especially the Chilling Hours Model respond much more sensitively to

[7] Darbyshire, R., Webb L., Goodwin I., Barlow S. 2011. Winter chilling trends for deciduous fruit trees in Australia. Agricultural and Forest Meteorology 151: 1074-1085

differences in temperatures than the Dynamic Model. This high sensitivity does not seem to accurately reflect how trees perceive such differences. Source: *Adapted from Luedeling et al. (2009)*[8]

Grapevine

The phenological models most commonly used for grapevine are variants of the Thermal time model. Models differ in the starting date (t_0), and the base temperature (T_b) considered to calculate GDD needs of each variety. Moreover, T_b can be universal or cultivar-specific. Temperature data required for the models is daily minimum and maximum (usually capped at 32ºC) temperatures.

- **GFV or Grapevine Flowering Veraison** (Parker et al., 2013[9]): The most comprehensive model available for grapevine up to date, it has been parameterized for ≈100 grapevine cultivars using a database spanning 55 years and >100 sites (the main viticultural regions in France plus Switzerland, Northern Italy and Greece). The model counts GDD from 1 March (DOY 60) using a T_b=0ºC and can estimate bloom and veraison dates. Reported accuracy for most varieties is <±3 days for bloom and <±5 days for veraison. In warmer climates, such as most of Spain, central or Southern Italy, and particularly south of latitude 41º N, the model tends to provide estimates at least 10-15 days in advance of the real dates.
- **GDD model**. The “classic” model for grapevines, counts GDD from 1 January, and uses a T_b=10ºC. The reference GDD values for each cultivar depend on the region for which the model has been adjusted. García de Cortazar-Atauri et al, (2009[10]) provide GDD requirements for budbreak and 10 varieties (from very early to very late ones) adjusted for the main viticultural areas in France and is particularly suitable for temperate-cool and cool regions. Van Leeuwen et al. (2008[11]) provide requirements for budbreak, bloom and veraison in >30 varieties, adjusted for warmer regions (Southern France and Northern Spain).

Stonefruit / Pomefruit

In these species, the phenological models most commonly evaluated correspond to the sequential type. In Table 2, a summary of models adjusted for pome and stone fruit species in European climates is presented. The models in the table require hourly temperature data, estimate forcing heat requirements as GDH using a base temperature usually around 4.5ºC and differ in how they estimate chill satisfaction (by counting Chill Units or Chill Portions) and in the general approach (sequential, or chill overlap).

[8] Luedeling, E., Blanke, M. and Gebauer, J-, 2009. Auswirkungen des Klimawandels auf die Verfügbarkeit von Kältewirkung (Chilling) für Obstgehölze in Deutschland (Climate change effects on winter chill for fruit crops in Germany). Erwerbs-Obstbau 51:81-94.

[9] Parker, A. et al. 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. https://doi.org/10.1016/j.agrformet.2013.06.005

[10] García de Cortazar-Atauri, I, et al. 2009. Performance of several models for predicting budburst date of grapevine (Vitis vinifera L). International Journal of Biometeorology 53:317-326. https://doi.org/10.1007/s00484-009-0217-4

[11] Van Leeuwen, C, et al. 2008. Heat requirements for grapevine varieties is essential information to adapt plant material in a changing climate. *VIIème Congrès International des Terroirs Viticoles - Comptes rendus - Volume 1.* 222-227

Table 2. Summary of some phenological models adjusted for European conditions to estimate bloom in stone and pome fruit trees

Crop	Type[1]	Nº Varieties	Region	Climate conditions	Chill models[1, 2]	Author[12]
Peach	S	1	SE Spain	Warm, Mediterranean	CU	Mounzer *et al.*, (2008)
	S	5	NW Italy	Temperate-cool	CH, CU	Valentini *et al.*, (2004)
	S	3	NE Spain	Temperate, Mediterranean	CU, **CP**	Miranda et al., (2013)
Almond	S	10	SE Spain	Warm, Mediterranean		Egea *et al.*, (2003)
Apricot	S	10	SE Spain	Warm, Mediterranean	CH, CU, **CP**	Ruiz et al., (2007)
	S	5	NW Italy	Temperate-cool	CH, CU	Valentini et al (2004)
Cherry	S	7	SE Spain	Warm, Mediterranean	CH, **CU, CP**	Alburquerque *et al.* (2008)
Japanese Plum	S	11	SE Spain	Warm, Mediterranean	CH, CU, **CP**	Ruiz *et al.*, (2018)
Apple	S, **CO**	1	10 sites	Warm to cool	CP	Darbyshire *et al.*, (2017)
	S	9	NE Spain	Temperate, Mediterranean	CP	Funes *et al.*, (2016)
	S	1	7 sites	Mediterranean to cool	TF	Legave *et al.*, (2013)
	S	4	Germany	Temperate to cool	CR	Chmielewski *et al.*, (2011)
	S	1	NW Italy	Cool	CU	Rea and Eccel, (2006)
	S	15	NW Italy	Cool	CU	Valentini *et al.*, (2001)

1. S: Sequential, CO: Chill Overlap. Models in bold had the best performance. rates

2. CU: Chill Units, CP: Chill Portions, CH: Chill Hours, TF: triangular function, CR: Chill. In bold, the best performing model

[12] Sources:

Alburquerque, Nuria et al. Chilling and Heat Requirements of Sweet Cherry Cultivars and the Relationship between Altitude and the Probability of Satisfying the Chill Requirements. *Environmental and Experimental Botany* 64.2 (2008): 162–170.

Chmielewski, Frank M. et al. Phenological Models for the Beginning of Apple Blossom in Germany. *Meteorologische Zeitschrift* 20.5 (2011): 487–496.

Darbyshire, Rebecca et al. A Global Evaluation of Apple Flowering Phenology Models for Climate Adaptation. *Agricultural and Forest Meteorology* 240–241 (2017): 67–77.

Egea, J. et al. Chilling and Heat Requirements of Almond Cultivars for Flowering. *Environmental and Experimental Botany* 50 (2003): 79–85.

Funes, Inmaculada et al. Future Climate Change Impacts on Apple Flowering Date in a Mediterranean Subbasin. *Agricultural Water Management* 164 (2016): 19–27.

Legave, Jean Michel et al. A Comprehensive Overview of the Spatial and Temporal Variability of Apple Bud Dormancy Release and Blooming Phenology in Western Europe. *International Journal of Biometeorology* 57.2 (2013): 317–331.

Miranda, Carlos, Luis G. Santesteban, and José B. Royo. Evaluation and Fitting of Models for Determining Peach Phenological Stages at a Regional Scale. *Agricultural and Forest Meteorology* 178–179 (2013): 129–139.

Mounzer, Oussama H. et al. Growth Pattern and Phenological Stages of Early-Maturing Peach Trees under a Mediterranean Climate. *HortScience* 43.6 (2008): 1813–1818.

Rea, Roberto, and Emanuele Eccel. Phenological Models for Blooming of Apple in a Mountainous Region. *International Journal of Biometeorology* 51.1 (2006): 1–16.

Ruiz, D., J. A. Campoy, and J. Egea. Chilling and Heat Requirements of Apricot Cultivars for Flowering. *Environmental and Experimental Botany* 61 (2007): 254–263.

Ruiz, David et al. Chilling and Heat Requirements of Japanese Plum Cultivars for Flowering. *Scientia Horticulturae* 242.August (2018): 164–169.

Valentini, N. et al. Chilling and Heat Requirement in Apricot and Peach Varieties. *Acta Horticulturae* 636 (2004): 199–20.

Valentini, Nadia et al. Use of Bioclimatic Indexes to Characterize Phenological Phases of Apple Varieties in Northern Italy. *International Journal of Biometeorology* 45.4 (2001): 191–19.

funded by European Commission

Citrus

Available models in this species have been adjusted for Florida (USA) growing conditions. Albrigo et al (2002)[13] adjusted a phenological model for *Citrus* bloom time in Central Florida. The model estimates the proportion of buds reaching bloom related to GDD (daily temperatures required). The cumulative developmental fractions estimate proportion of buds opening from 0 to 100%, using three temperature ranges: below 12.8ºC, between 12.8 and 20.8ºC and above 20.8ºC.

Soft fruit

Several different models have been reported across soft fruit for estimating chill unit accumulation and these include, the Thermal time and Utah models and the Landin model (assumed effectiveness of model based on exponentially decreasing temperatures). Some research has indicated that there should be species and possibly even cultivar specific chill models which would be based on a defined physiological basis as there are no one size fits all models currently available.[14] Strawberry tends to follow GDD model for heat accumulation.

Discussion

As shown above, it is difficult to make an accurate determination of the standard critical temperatures for bud injury. Due to the many factors influencing the response of a bud to low temperatures, and because the characteristics of spring frost (duration, minimum temperature, and the rate at temperature increases and decreases) are highly variable, it is very difficult to accurately predict the degree of injury, which may occur following a spring frost by using temperatures alone. Consequently, when critical temperatures are used in making decisions as to when to begin active frost protection, caution is advised, and a prudent measure would be to take them only as a guideline.

Chilling and forcing heat models have been combined to predict budbreak or bloom in fruit crops. For pomefruit and stonefruit, several different models are available, focused mainly on predicting just bloom dates. In essence, most models use the same assumption, in which chill requirements must be satisfied first in order to accumulate heat (what is called a ‘sequential model’). The main difference between them lies in how chill is calculated. The ‘classic’ method, chill hours below 7ºC, is highly inefficient, particularly for warm regions and in climate change scenarios, as it disregards temperature ranges that are now known to contribute to the fulfilment of chilling requirements. Chill Units (Utah or Anderson model) perform better for a wider range of climates, and it could be considered as the ‘reference’ method nowadays, but it is ill-suited for warm or Mediterranean conditions. To date, Chill portions is the best existing model for most growing regions, so chill fulfilment should preferably be calculated using this method, especially when transferring varieties from one region to another. Switching to Chill overlap methods could provide more reliable phenology estimates, as found in ‘Golden Delicious’ apple.

For grapevine, mainly two approaches are used (GDD and GFV models), both consider just heat accumulation from a fixed date and differ in the date (1-Jan or 1-March) and base temperature (0°C or 10°C). The models provide reasonably good estimations for bloom (GDD also for budbreak) under temperate and cool climates, but in warm and Mediterranean regions, the estimated dates are too early (up to 2 weeks) to use the general formulation of the models or the same values. In GDD model, reference values for warm regions are available. These improve the accuracy of the estimates, but the expected error can still be too high.

[13] Albrigo L.G. et al. Flowering expert system development for a phenology based citurs decision support system. Acta Horticulturae 584 (2002):247-254.
14 Atkinson et al., 2004

funded by European Commission

Conclusions

The understanding of physiological processes in plants that are related to spring frost can help farmers to better estimate the risk of frost damage and take – as far as possible – correspondent measures.

For all cultures, the following points can be summed up:

- Phenology and development of plants follow inner stimuli (i.e. phytohormones) and outer conditions (i.e. temperature, day length). Perennial plants are therefore distinctively affected by unusual weather conditions due to climate change. Especially warm conditions at the end of dormancy (early spring) can result in early budbreak or bloom and end in high risk situations for spring frost.
- Stress avoidance in general enhances the capability of plants to cope with unfavourable conditions.
- Susceptibility of plants to spring frost depends on the phenological stage. Date of budbreak or bloom can be influenced by the choice of species or cultivar, the rootstock-variety combination and site selection.
- Nutrition state influences the degree of frost damage. Especially a balanced supply with nitrogen and potassium is vital. Oversupply with nitrogen should be avoided, as it enhances susceptibility to frost.
- If components used (rootstock/scion) are taken from different climatic zones, a strong rootstock influence is usually observed. For instance, peach cultivars grafted on Prunus mandshurica is known to be delayed 7-10 days in flowering/fruit ripening time. For species which rootstock and scion are familiar with their climatic habitat, the differences will be not evident, especially from a practical point of view (2-3 days difference in flowering phenology). It is typical for apples and grapes. To sum up, it is possible to find the 'delaying rootstock' within the 1st group, however side effects such as increased incompatibility of grafts, should be considered. Furthermore, it is not applicable for early cultivars.
- Phenological models are not complete enough to be used in decision support systems (DSS), as they estimate usually just bloom (sometimes include budbreak).

Research needs

- Use of the Dynamic Model for chill accumulation is widely recommended, but it is difficult to use and procedures for adapting the models to new species and cultivars are not available. This gap needs to be closed. There is a need for models covering the full range from the end of latency-postbloom.
- The usability of phenological models is, especially for warmer or Mediterranean conditions or specific cultivars, restricted. Adaption and validation for particular climate or cultivar characteristics with the help of long-term observations of phenological stages would be helpful.
- Plant biology and physiology is lacking in the existing models.
- Better markers are needed for deciding when the different stages of the dormancy season begin and end. At present, climatic requirements rely on unreliable guesses for these points in time, which incurs risks of substantial errors.
- Implication of models in DSS and risk assessment tools could be an interesting subsequent feature.

Ideas for operational groups and other innovative projects

- Development of procedures to adapt models for new species and cultivars
- Improve and complete models by taking into consideration more plant biology and physiology
- Search for physiological markers to determine the start and end of dormancy stages (compare MP 5A)
- Collect available field data on plant phenology and corresponding weather data from different climate conditions. Compile this data in a database, that can be shared and is available open source. This data could be used to calibrate and improve models. The objective is to gather and connect all the different investigations scattered all over Europe about phenological stages
- Development of phenology prediction for orchards and vineyards and implementation in DSS and risk assessment tools.

funded by European Commission

Further research needs coming from practice, ideas for EIP AGRI operational groups and other proposals for innovation can be found at the final report of the focus group, available at the FG webpage **https://ec.europa.eu/eip/agriculture/en/focus-groups/protecting-fruit-production-frost-damage**

funded by European Commission