



Review

Temperate Fruit Trees under Climate Change: Challenges for Dormancy and Chilling Requirements in Warm Winter Regions

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Abstract: Adequate chill is of great importance for successful production of deciduous fruit trees. However, temperate fruit trees grown under tropical and subtropical regions may face insufficient winter chill, which has a crucial role in dormancy and productivity. The objective of this review is to discuss the challenges for dormancy and chilling requirements of temperate fruit trees, especially in warm winter regions, under climate change conditions. After defining climate change and dormancy, the effects of climate change on various parameters of temperate fruit trees are described. Then, dormancy breaking chemicals and organic compounds, as well as some aspects of the mechanism of dormancy breaking, are demonstrated. After this, the relationships between dormancy and chilling requirements are delineated and challenging aspects of chilling requirements in climate change conditions and in warm winter environments are demonstrated. Experts have sought to develop models for estimating chilling requirements and dormancy breaking in order to improve the adaption of temperate fruit trees under tropical and subtropical environments. Some of these models and their uses are described in the final section of this review. In conclusion, global warming has led to chill deficit during winter, which may become a limiting factor in the near future for the growth of temperate fruit trees in the tropics and subtropics. With the increasing rate of climate change, improvements in some managing tools (e.g., discovering new, more effective dormancy breaking organic compounds; breeding new, climate-smart cultivars in order to solve problems associated with dormancy and chilling requirements; and improving dormancy and chilling forecasting models) have the potential to solve the challenges of dormancy and chilling requirements for temperate fruit tree production in warm winter fruit tree growing regions.

Keywords: deciduous fruit trees; bud phenology; bud dormancy; endo-dormancy; para-dormancy; eco-dormancy; chilling hours; Utah model; dynamic model

1. Introduction

Climate change refers to any long-term changes in climate status (i.e., decades or longer) such as global atmospheric CO₂ or mean temperature due to human activities or natural variability [1]. Climate change is defined in the United Nations Framework Convention on Climate Change (UNFCCC) as “a change of climate which is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and which is in addition to natural climate variability observed over comparable time periods” [2]. Climate change is considered one of the most impactful phenomena on the production of temperate fruit crops [3]. All climatic elements affect plant growth, development and the productivity of different fruit crops. Temperate fruit crops undergo several physiological processes related to winter dormancy and chilling requirements; this is especially the case under tropical and subtropical conditions [4]. The major effect of climate change on temperate fruit crops may be attributed to increased atmospheric CO₂ (413.95 ppm, December 2020) and temperature (0.97 °C, November 2020) [1,5].

Temperate fruit trees originate from different locations characterized by four well-defined seasons (spring, summer, fall and winter) with a very cold winter and warm spring–summer seasons for the dormancy and growth periods, respectively [6]. Temperate fruit trees account for about 48% of global fruit production, and therefore generate essential revenue and food [7]. Temperate fruits are adapted to the temperate zone climate in mid-latitudes [8]; however, about 50% of temperate fruit are cultivated in different climatic zones in China, Turkey, USA, Brazil, Italy, and Spain; these countries make up most of the world’s total production [9]. The rapid climatic changes that have occurred during the last few decades have led to undesirable physiological changes such as abnormal bud break, advanced or delayed flowering, interrupted fruit growth and ripening, and advanced leaf senescence [10]. Climatic changes may also alter the adaptability and sustainability of temperate fruit trees to their production regions. This is inciting scientists to develop strategies that may improve the adaptability of trees to such changes, particularly winter warming, which may be helpful in the interpretation of some ambiguous physiological and biochemical dormancy-related issues [11].

Dormancy, as a plant developmental phase, occurs in deciduous fruit trees to overcome the unfavorable environmental (e.g., weather) conditions that occur during winter [12–14]. Several trials have evaluated the role of various bioactive compounds in compensating for the chill deficit for dormancy breaking [15]. Most research during the past five decades has focused on phenology modeling, where it may be possible to correlate plant phenological events with the surrounding temperature in order to identify the most effective temperature range to break dormancy [16,17]. Lang et al. [18] proposed different dormancy terminologies to distinguish among the various types of bud dormancy. Para-dormancy is growth suppression due to the effect of an inhibitor transported from one plant part to another one (e.g., apical dominance). Endo-dormancy describes growth inhibition related to a chill deficit; in this case, buds never open, even if all other climatic conditions are suitable. Eco-dormancy refers to growth inhibition due to insufficiently warm temperatures after winter. By the beginning of the 21st century, dormancy research had expanded to the molecular level to discover dormancy-related genes, such as Mads-box (DAM) in peach (*Prunus persica*) [19]. Gene expression research associates dormancy with hormonal and metabolic changes during the dormancy period [20]. Epigenetics (the modification of the gene expression without any change of gene sequences) is considered a promising mechanism for dormancy breaking [21]. Reactive oxygen species (ROS) were demonstrated to be key molecules, integrating metabolic processes and environmental cues in regulating physiological and phenological plant stress processes [22].

Temperatures on Earth are predicted to rise up to 6 °C by the end of this century, compared to those in the pre-industrial era [23]. This agroclimatic metric is unlikely to remain stable [24]. The advanced trend in the blooming time of several fruit trees indicates that the dormancy breaking process is significantly changing, most likely in response to climate change [25]. Plant breeding techniques to develop new cultivars suited for such

a change in temperature would be a proper solution, but this may be a long process; therefore, other proper practices may be faster solutions at present. Dormancy breaking chemical products have been used in a wide range of applications to enhance earlier budburst in deciduous fruit trees [26]. These products include, for instance, mineral oils, cyanamides, thiourea, potassium nitrate, and growth regulators such as gibberellic acid and cytokinins [27]. Although current research studies on dormancy have made good progress to unveil and clarify some unclear issues [28], a comprehensive framework that integrates knowledge between dormancy and climate change for a clearer perspective is still missing.

Therefore, the aim of this review was to discuss the events relating to dormancy and chilling requirements of temperate fruit trees in warm winter regions in light of global climatic change.

2. Climate Change and Temperate Fruit Productivity

It is fundamental knowledge that the yield of temperate fruit trees, like that of other horticultural crops, is controlled by climate elements such as temperature, humidity, atmospheric CO₂, precipitation, wind speed, sunlight, and UV index. Among these, temperature and atmospheric CO₂ are the most highlighted climate elements for temperate tree crops. Extensive research in tree phenology has demonstrated that the increase in temperature and atmospheric CO₂ levels ultimately influences the number of chill hours required for dormancy breaking and the yield and fruit quality of temperate fruit crops [10,29–43] (examples are given in Tables 1 and 2).

Table 1. Some examples for the impacts of elevated temperature on deciduous fruit tree crops including countries and literature references (Ref.).

Crop	Country	Impact	Ref.
Apple (<i>Malus × domestica</i> Borkh)	Morocco	Late blooming, extended blooming period, extended period from blooming to harvest, and reduced fruit quality were recorded.	[29]
Apple (<i>Malus × domestica</i> Borkh)	India	Negative effects on cumulative chilling requirements and final fruit set as well as variation in flowering onset and duration were recorded.	[30]
Apple (<i>Malus × domestica</i> Borkh) and Almond (<i>Prunus dulcis</i> (Mill.) Webb)	Spain	A phenology disruption was recorded due to changes in chilling requirements and mean temperature threshold for spring growth.	[31]
Apple (<i>Malus × domestica</i> Borkh)	Germany	Insufficient chilling requirements negatively affected flowering date and quantity. Early spring frost damages the new flush.	[32]
Apple (<i>Malus × domestica</i> Borkh)	Iran	Expected temperature range of tree growth will change from 11.6–27.3 to 16.7–33.4 °C by 2090, and 46.7% of orchards will be lost.	[33]
Apple (<i>Malus × domestica</i> Borkh) and other fruit crops	USA	Increased frequencies of longer warmer summers can increase the insect generations during the season and the over-wintering survival of insect pests and their natural enemies.	[34]
Apple (<i>Malus × domestica</i> Borkh)	Spain	Continuous vulnerability to insufficient chilling will lead to late blooming by the end of the 21st century.	[35]
Apple (<i>Malus × domestica</i> Borkh)	India	A negative fruit production rate was shown from 2005 to 2014 by 0.183 ton ha ⁻¹ year ⁻¹ .	[36]
Apple (<i>Malus × domestica</i> Borkh)	India	Insufficient chilling negatively affected flower bud induction, fruit set, yield, color, firmness, and taste. Cold temperature during flowering affected pollination. Insufficient chilling also posed serious problems such as apple scab epidemics, red spider gradation, and premature leaf fall.	[10]

Table 2. Some examples for the impacts of elevated CO₂ on some fruit crops including countries and literature references (Ref.).

Crop	Country	Impact	Ref.
Grapevine (<i>Vitis vinifera</i> L.)	Spain	Fruit quality (mainly contents of phenolic compounds and total soluble solids) of some old genotypes was quite stable at CO ₂ (700 ppm) and temperature (4 °C).	[37]
Peach <i>Prunus persica</i> L.	Spain	Decreased stomatal conductance, alleviated drought stress effects, and an increased photosynthetic rate were recorded.	[38]
Grapevine: (<i>Vitis vinifera</i> L.), cv. Tempranillo	Spain	CO ₂ (700 ppm) decreased the combining effects of temperature on the anthocyanin content and sugar ratio. Elevated CO ₂ and air temperature was expected to advance grape maturity and reduce the elapsed period between fruit set and maturity.	[39]
Grapevine (<i>Vitis vinifera</i> L.)	Croatia	Grapevine phenology was advanced by 4.1 and 6.8 days at 4 °C and ambient temperature, respectively, and early fruit maturity and ripening were reported.	[40]
Grapevine (<i>Vitis vinifera</i> L.)	Spain	Elevated CO ₂ (700 ppm) for 10 days decreased chlorophyll content, but the effect dissipated after longer exposure for 20 days. Decreased N content and no effect on chlorophyll a/b ratio were reported.	[41]
Peach (<i>Prunus persica</i> L.) Batsch	China	Elevated CO ₂ (360 ppm) increased fruit sucrose, lactones, and flavor constituents (linoleic and linolenic acid, pyruvic acid, and the precursor of volatile compounds) but decreased malic acid.	[42]
Pears (<i>Pyrus pyrifolia</i> Nakai), cv. Niitaka	Korea	Elevated CO ₂ (700 ppm) increased fruit weight, photosynthetic rate, and total soluble solids content at harvest.	[43]

Several studies have evaluated the productivity of temperate fruit crops with the current status of global climate change [4,33,44–53]. These studies addressed the various challenges that impact temperate fruit production [4]. It was reported that changes in both agroclimatic and temperature indices were higher than the vulnerability threshold of apple production [33]. Research has focused on different phenological stages such as bud swelling, the onset and end of blooming of apple and pear trees [44], as well as the adaptability of fruit crops to climate change conditions [45]. In this regard, an evaluation of various adaptation strategies for grapevines was conducted [46–49]. The projected impacts of climate change on frost effect for some temperate-zone-grown crops such as almond, avocado, and orange were also studied through evaluating plant requirements of energy and water to mitigate frost damage [50]. Climate change impacts on yield and phenology of hazelnut trees in the maritime climate of Australia were also discussed [51]. The impact of climate on plant phenology as a decisive factor in defining the geographical range of fruit crops was evaluated for peach to create an ecological thermal niche map [52]. In addition, apple-based agroforestry systems for C-sequestration and biomass production were reported with the effect of climate change in the temperate region of Northern Himalaya, India [53]. Bioclimatic indices and plant phenology models assessing the suitability of temperate fruit species to adapt to climate changes were used to provide spatial and temporal information regarding the future changes in fruit quality [3]. In this regard, a model study revealed future climate changes and their effects on plant phenology of temperate deciduous trees in spring [17], including the role of climate changes in the re-distribution of cultivated temperate fruit crops, based on chilling accumulation [7]. It is also important to note that climate changes could lead to changes in the plant phenological processes (Figure 1) and susceptibility to different species of pests and diseases [10,34], which may negatively impact total crop yield and quality.



Figure 1. Dormancy and key phenological stages of apple and sour cherry trees up to harvest, which can be seriously affected by climate change. Key growth stages for apple: dormancy (1), silver tip (2), pink tip (3), blossom (4), pollination (5), petal fall (6), fruit set (7), fruit growth (8), and mature fruit (9). Key growth stages for sour cherry: dormancy (a), bud swelling (b), pink tip (c), full bloom (d), pollination (e), petal fall (f), fruit set (g), and mature fruit with anthracnose disease (h).

3. Understanding the Role Dormancy

It is a natural phenomenon in deciduous fruit trees that dormancy occurs during the coldest period/season of the year, at which point growth is halted with modified cell physiology to avoid damage caused by cold temperature [7]. The decline in temperature and photoperiod during winter induces vital biological processes during dormancy that ultimately affect plant re-growth in spring [54]. This phenomenon was extensively studied from different perspectives [11,14,55] as a type of plant resistance to severe reduction in temperature [15]. During dormancy, trees show no visible growth and minimize all physiological processes during winter, and eventually resume growth in spring [11]. Physiological-wise, the trees can recognize the fluctuation in temperature among the seasons. Thus, trees start dormancy as the temperature decreases in late fall and early winter and then begin re-growth as the temperature increases in spring after being vulnerable to particular chilling hours during winter [12,56]. Each temperate fruit cultivar has certain

agroclimatic phenological process requirements for the spring to fall seasons [7]. Each cultivar has its own chilling and warmth requirements, as reported for many species such as pome fruits and nuts, and such information is considered in the planting of a specific cultivar in a given growing area [55]. Researchers investigated the physiological mechanisms of extended dormancy in spring alongside the rise in temperature [57,58]. Buds undergo various physiological changes during dormancy until flowering in spring [59]. However, unfavorable conditions (such as severe cold, drought, or salinity) may induce the physiological events of extended dormancy (eco-dormancy) [6]. Extended dormancy could also occur as a result of hormonal imbalance such as growth promoting hormones, gibberellins, and growth retardants (e.g., abscisic acid) even under suitable weather conditions. This event results in stopping plant growth and blooming (para-dormancy) [14,18]. Dormancy can also occur when insufficient chilling requirements in winter or warm temperature in spring causes an extended dormancy (endo-dormancy) [57,60]. This event is considered the most limiting blooming factor in deciduous fruit trees and may lead to reduced fruit set with increased percentage of malformed fruit affecting total fruit yield [14]. Therefore, the physiological, biochemical, and molecular aspects of flower bud dormancy for temperate fruit species are essential factors in successful fruit production, especially under climate change conditions [61].

3.1. Dormancy Breaking Chemical Compounds

Under temperate climatic conditions, deciduous fruit trees need certain chilling hours during winter for dormancy breaking by the beginning of spring. Chilling requirements differ from one species/cultivar to another, and inadequate chilling hours may lead to several physiological disorders such as uneven bud break, weak vegetative growth, partial anthesis, and poor flower development [13]. Therefore, insufficient chilling hours of a fruit tree in a mild-winter region could be compensated through exogenous application of some chemical products [13] such as copper sulphate (10%), zinc sulphate (5%), and urea (10%) during the period from September to January [62]. These products are commonly categorized as S-based (e.g., copper sulphate, zinc sulphate), N-based (e.g., potassium nitrate, calcium cyanamide, hydrogen cyanamide (HC), sodium azide, urea), and S- and N-based chemical components (e.g., thidiazuron) [63], of which some examples are given in Table 3.

3.2. Dormancy Breaking Organic Compounds

There are several organic compounds that can be applied to trees for dormancy breaking such as mineral oil, garlic extract, and thiourea [64,65]. Due to environmental concerns and toxicity of some chemical compounds, organic compounds have been used for breaking bud dormancy such as cinnamon, coffee, ginger, clove, colocynth, olive, garlic, red chilies, nigella, and turmeric extracts [66], of which some examples are given in Table 3. These organic agents are rich in volatile compounds, pigments, tannins, phenols, antioxidants, vitamins, and nutrients [66].

The recent advancement in organic farming has increased the demand for dormancy breaking organic compounds as safe alternatives for the chemical ones. Garlic (*Allium sativum* L.) extract is considered as one of the most effective organic compounds for dormancy breaking [67–69]. The application of garlic extract either alone (5–10%) or combined with mineral oil (2–4%) was highly effective in dormancy breaking of grape, apple, and kiwifruit [67–69]. Foliar application of garlic extract (1%) induced 5-day-early bud break in peach [70]. The promotive effect of garlic extract is mainly related to its sulfur constituents: di-allyl-sulfides (mono-, di- and tri-), and dimethyl disulfide [68]. The application of fresh garlic extract, garlic oil, or di-allyl-sulfide stimulated dormancy breaking in grapevine without causing phytotoxicity in seedlings [68]. Garlic extract is rich in sulfur molecules, which produce cysteine as a result of reduced sulfur [69]. Cysteine metabolism leads to glutathione, which detoxifies ROS and free radicals. The reduced glutathione can promote the up-regulation of the transcription of 1,3- β -D-glucanase, which is considered as a funda-

mental enzyme in the mechanism of dormancy breaking [71]. The exogenous application of reduced glutathione showed promoted bud break in grapevines [72].

S-methyl cysteine sulfoxide led to 100% dormancy breaking in buds of various table grape cultivars [73]. Foliar sprays of onion extract on apple promoted bud break, reduced the number of days to full bloom, and increased the contents of total free amino acids, hydrogen peroxide, proline, auxins, and anthocyanin but reduced catalase activity and free phenol content [64].

Combinations of amino acids, polysaccharides, nitrogen, and calcium (e.g., Bluprins, Biolchim Spa, Bologna, Italy) can work as bud dormancy breaking agents [74] and can cause bud break induction and uniform flowering in grapes, cherries, and kiwifruit [75]. In a four-year comparative study, the combined solution of mineral oil (3.5%) + HC (0.35%) was more effective on bud break of apple cultivars “Maxi Gala” and “Fuji Suprema” compared to Bluprins, but all treatments showed significant results compared to the control plots [21].

Table 3. List of some dormancy breaking compounds, their applied and effective concentrations, used crops, and literature references (Ref.).

Compound	Application Time	Applied Concentrations (Effective Concentrations)	Crop (Scientific Name)	Ref.
Potassium nitrate (KNO ₃)	During germination	0.2, 1, and 3% (0.2%)	Agrimony (<i>Agrimonia eupatoria</i> L.)	[76]
Gibberellic acid (GA ₃)	During germination	100, 200, and 300 mg L ⁻¹ (100 mg L ⁻¹)	Agrimony (<i>Agrimonia eupatoria</i> L.)	[76]
Hydrogen cyanamide (HC)	During bud cutting	5% for 4-year-old cuttings	Grapes (<i>Vitis vinifera</i> L. × <i>Vitis labruscana</i> Bailey)	[77]
GA ₃ or KNO ₃	During pre-germination	Seeds soaking in GA ₃ (400 ppm) for 24 h or KNO ₃ (1 M) for 30 min	Highland papaya (<i>Vasconcelle aquercifolia</i> L.)	[78]
GA ₃	During seed priming	Seeds primed in GA ₃ (750 ppm) for 48h	Common poppy (<i>Papaver rhoeas</i> L.) and	[79]
KNO ₃	During seed priming	Seed treatment with KNO ₃ (0.5 g L ⁻¹) for 24 h	(<i>P. dubium</i> L.)	
GA ₃ or KNO ₃	During germination	Dormant seeds treated with GA ₃ (150 ppm) or KNO ₃ (1000 ppm) for 24 h.	Wall rocket (<i>Diplot axiserucoides</i> L.)	[80]
Garlic extract (GE) or HC	Before winter dormancy	Cuttings immersed in GE (10%) or HC (4%) (<i>v/v</i>) for 10 s	Grape (<i>Vitis vinifera</i> L.)	[68]
HC (Dormex)	During bud cutting	6-year-old cuttings treated with HC (5%)	Grape (<i>Vitis vinifera</i> L. × <i>Vitis labruscana</i> Bailey)	[13,64]
GA ₃	During germination	Seed soaking in GA ₃ (10, 100, or 1000 mg L ⁻¹) and scoring at 30 d	Ashitaba (<i>Angelica keiskei</i>)	[81]
Zinc sulphate (ZnSO ₄)	Before winter dormancy	Foliar application (1000, 1500, and 2000 mg L ⁻¹) (2000 mg/L)	Kiwifruit (<i>Actinidia deliciosa</i> L.)	[82]
HC	45 days before natural bud break	2, 4 and 6% (4%) + mineral oil (2%)	Kiwifruit (<i>Actinidia deliciosa</i> L.), cv. Hayward	[83]
Erger Biostimulant	At week no. 5, 9, and 13 from bud break	Foliar application (6%) once at three different times in fall	Kiwifruit (<i>Actinidia deliciosa</i> L.)	[84]
KNO ₃ or GA ₃	At stratification of seeds	Seed soaking in KNO ₃ (0.2%) or GA ₃ (5 mM)	Apple (<i>Malus domestica</i> L.), cv. Ligol	[85]
HC	In late August	Foliar application (12.5 mM)	Grapevines (<i>V. vinifera</i> L. × <i>V. labruscana</i> Bailey), cv. Kyoho	[86]
HC, KNO ₃ , mineral oil, thiourea, or Ca(NO ₃) ₂	In December	Foliar application of HC (4%), KNO ₃ (8%), mineral oil (6%), thiourea (2%), or Ca(NO ₃) ₂ (6%)	Apple (<i>Malus sylvestris</i> Mill), cv. Anna	[64]

3.3. Some Aspects of the Mechanism of Dormancy Breaking

The seed or bud dormancy breaking mechanism is a vital biological process for the proper timing of flowering and fruiting and hence the survival of a plant species in its geographical zone [63]. Dormancy breaking in seeds is often hampered by a hard seed cover, a mechanical dormancy that greatly prevents moisture absorption, while in some other species, seeds may have undergone physiological dormancy, which hinders seed germination due to internal factors (i.e., hormonal imbalance) [87]. Seed dormancy is an adaptation strategy for several plant species to survive the unfavorable environmental conditions [88]. Bud dormancy in deciduous fruit trees is a crucial plant phase that is mainly related to cold temperature in the winter season and the accumulation of specific cold hours that eventually trigger bud growth due to the warm temperature in spring [89]. Phytohormones such as indole-3-butyric acid (IBA), indole-3-acetic acid (IAA), gibberellins (GAs), and abscisic acid (ABA) play a crucial role in dormancy induction and breaking mechanisms of seeds and buds. During seed maturation, ABA induces dormancy, but GAs are essential in dormancy breaking [90]. The balance of both hormones and ROS regulates bud endo-dormancy, and buds resume their growth once they are exposed to sufficient chilling requirements [89,91]. Different oxidative and reductive reactions are important for dormancy breaking [92]. For example, foliar spray of HC inhibited catalase activity and led to increased levels of H₂O₂ that ultimately broke bud endo-dormancy [71]. Using thiourea has also showed increased levels of proline, putrescine, and biogenic amines (i.e., tryptamine, tyramine, histamine, methyl-butylamine, and serotonin), calcium, and ethylene but reduced levels of ABA that promoted bud break in apple trees [64,65,93]. Within 5 days of sprayed HC application to grapes, a dramatic rise in starch hydrolysis and soluble sugar contents in buds and internodes was noticed. The reduction in starch content was accompanied with an induction in α -amylase activity, and flowering time was dependent on the rate of sugar accumulation in buds [94]. Dormex (AlzChemTrostberg GmbH, Trostberg, Germany) can release cyanide (CN), which also increases due to the role of other enzymes (e.g., glucosidase, lyase), associated with increased levels of ROS in the cytosol that eventually affect gene expression related to dormancy breaking [22]. When chilling requirements are fulfilled, dormancy-associated (DA) transcript levels are also affected, so dormant flower buds start to accumulate heating hours, and then flowering takes place [24]. It was reported that GA4 could induce bud break in poplar (*Populus balsamifera* L.). Long-term chilling exposure is associated with GA biosynthesis and correlated with plant re-growth ability [95]. It was observed that GA4 application can compensate for chilling requirements and accelerate bud break in Japanese apricot through the inductive expression of important metabolites (e.g., galactose, glyoxylate, dicarboxylate, starch, sucrose) involved with energy metabolism and oxidation-reduction reactions (redox system) [96,97]. The complete series of bud dormancy starting from bud formation to flowering has been thoroughly described for various deciduous fruit crops [14,22,88,93,98–105].

4. Chilling Requirements

Chilling requirements could be defined as a certain range of hours at a specific cold temperature range required during winter for endo-dormancy breaking and re-growth by early spring [14]. The most important criteria when choosing cultivation sites in the warm winter fruit growing regions are the quality and/or quantity of chill during winter. Therefore, the cultivation of deciduous fruit trees species in a low-chill region may require the use of dormancy breaking agents, along with plant varieties that have low chilling requirements. After trees fulfill their chilling requirements and exit endo-dormancy, they also need sufficient heat hours for re-growth. Thus, it is important to find a strategy to calculate the chilling and heat requirements, and this may require experiments at a very large scale, which is impractical [29]. A very close relationship between dormancy and chilling requirements, particularly under the conditions of climate change, has been reported generally [14,106,107] but also at species level, e.g., apricot [108], apple and almond [109], sweet cherry [110] and pomegranate [111].

4.1. Chilling Requirements versus Climate Change and Warm Winter Conditions

Many species and cultivars of deciduous fruit trees require cold temperature during winter and warm temperature for endo-dormancy breaking in spring [112]. The effective chilling temperatures range from 0 to 7 °C for most deciduous fruit. Temperatures below 0 or above 7 °C are not sufficient to fulfill plant chilling requirements [113]. The initiation of vegetative and reproductive buds starts in summer and late fall, and then buds go into dormancy during winter when day length became shorter and temperature decreases [114]. The average Earth temperature is currently higher than it was 1200 years ago [115]; therefore, global warming affects temperate and polar latitudes significantly more than the equatorial ones [23]. It is expected that average temperature will increase over 4 °C by the end of this century [116]. In this regard, it is expected that problems related to floral bud induction will be more significant in the coming years, and this requires creating a novel system to understand the mechanism that induces bud break. Different fruit crops showed fluctuation in bud break and plant phenological stages because of climate change. For example, olive in Spain and Italy showed fluctuation in flowering pattern with temperature fluctuations between cold and warm winter, and this can provoke frost damage by the beginning of spring [117,118]. Global warming has induced early flowering of pear and apple trees in France due to the change in tree response to different chilling and heating temperature patterns, which enhance the development of floral primordia within buds and induce bud break [25]. The significant effect of global warming has been more pronounced by the end of winter and beginning of spring (February–March) since 1988. During this time, the mean temperature increased by 1.6 °C during early spring, and 0.8 °C during winter (November–December) [25]. Warm winter has extended the bud dormancy period causing fluctuation in bud break and phenological stages. This has affected flowering time and duration, pollen grain quality, pistil malformation, fruit yield, and fruit quality. Fruit size and weight were higher during seasons with cold winters, since fruit were subjected to sufficient chill [29]. In temperate climates, spring frost is considered the most important factor of crop damage. A temperature decline below zero for a few hours was sufficient to kill apricot flower buds in Hungary. In addition, early flowering resulted in floral damage and low fruit quality [119]. In the subtropics of India where there is insufficient chill during winter, most pear orchards remained unproductive even after plants reached maturation [120]. In general, global warming leads to less vigor in plants and reduction in fruit set, yield, size, color, juice content, and shelf life with increased pest infestation in apple [114,121]. Continuous insufficient chilling leads to physiological symptoms such as delayed foliation, low yield, and fruit physiological disorders [122]. Long drought periods during summer and reduced snowfall during winter have decreased the suitable area for apple cultivation, which has changed the flora in such areas because growers shifted to other cash crops [114]. This has also increased the need to replace temperate fruit species and cultivars grown in tropical and subtropical areas with others that have low chilling requirements [123]. Mild winter (subtropical) regions in the middle latitudes, which include the transition from tropical to temperate zones, are dominant areas for stone fruit production. Trees grown in mild winters may have fewer chilling units in some years and may also be damaged by spring frost in others. Therefore, these regions of mild winter have been classified into three zones according to chilling requirements: transitional zone (650–950 chilling units), medium-chill zone (400–650 chilling units), and low-chill zone (below 400 chilling units) [124]. In Egypt, apple trees that were artificially chill-treated at 7 or 10 °C continuously took about 600 hours for bud break [125]. Therefore, winter warming may increase heat accumulation rate, which could compensate for any phenology-delaying impacts of reduced chilling [107].

4.2. Models to Calculate Chilling Requirements

Many mathematical models have been developed to determine chilling requirements for different fruit tree species and cultivars in various growing regions (Table 4). The approaches of these models make them reliable and plausible, although they are not suitable

for all growing regions. An accurate model is essential for the quantitative development of suitable adaptation strategies of climate change for temperate fruit trees [126]. The use of many mathematical models is dependent on the plant species and growing regions, and new models are constructed for various climatic conditions (Table 4).

Simple classical models include the growing degree hours (GDH) model to calculate heat requirement [127]. Some other models simply count the “chilling hours” during winter by calculating hours below 7.2 or between 0 and 7.2 °C. However, these models neglect the unfavorable effect of warm winter temperatures on chilling-hour accumulation, especially in subtropical or tropical climates. This error was corrected by the “Utah model” for peach [128] and by using advanced statistical approaches, such as R language, to facilitate and standardize the use of various models [6]. Many other models were also developed to calculate winter chill. The time at which trees were exposed to cold temperature can be used to estimate the approximate date of dormancy breaking. The importance of predicting climate changes and their impact on available chilling hours is critical for deciduous fruit because well-established orchards are planted for many years, and it will take about 15–30 years obtain a full return when replacing these orchards with new cultivars with fewer chilling requirements [129]. In addition, breeding programs may also take several years to develop such new cultivars. Moreover, the qualitative characteristics of a new cultivar are the result of many factors (e.g., eco-pedology, cultivation methods, and cultural and socioeconomic parameters) that eventually affect its success in a specific area [28].

Chilling models use climate change scenarios to predict future chilling hours in a specific region. Knowledge of plant chilling requirements can be used in breeding programs to evaluate plant capability to adapt in different climates [28]. The outcomes of chilling models are largely dependent on the type of used model and the conditions of the growing region [11]. The choice of appropriate model is important for the determination of climatic change impacts on winter chill [130]. To determine the chilling requirements of a particular cultivar, two steps can be conducted (Figure 2). The first step is to establish a dormancy phase, and this can be carried out by running experiments or by statistical analyses. The second step is to calculate the chilling requirements using temperature-based models.

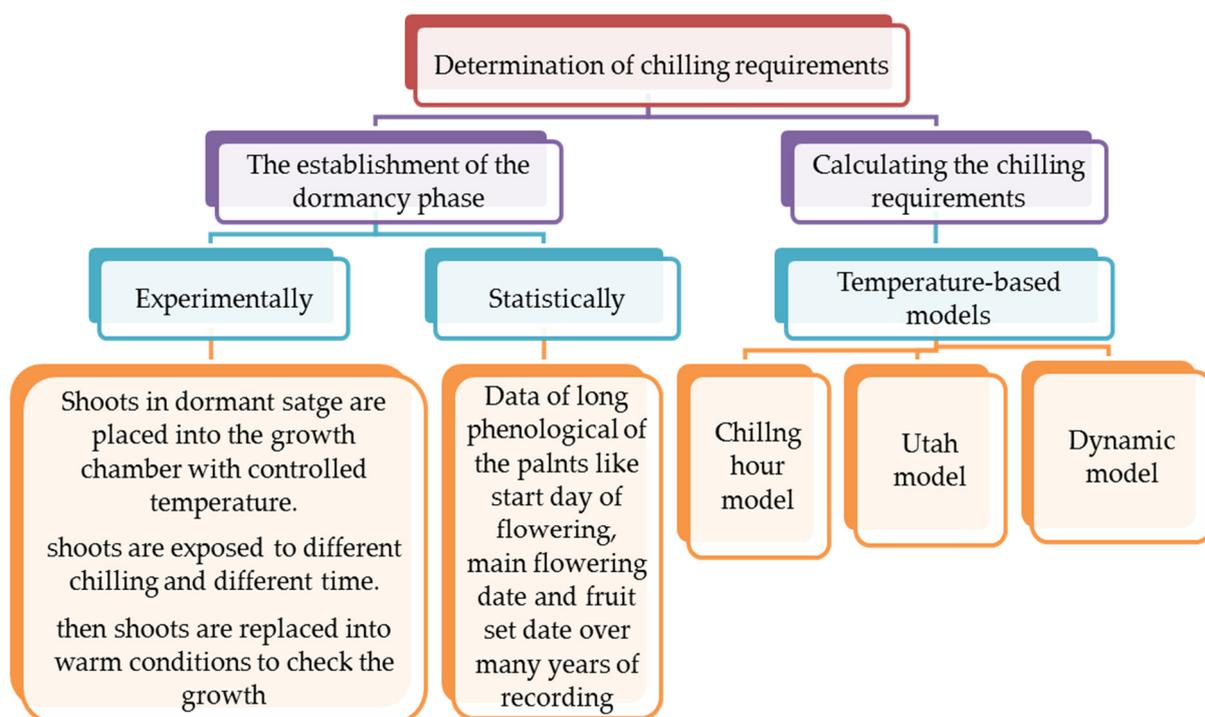


Figure 2. A chart flow for determination of chilling requirements for deciduous fruit trees.

Table 4. Names, descriptions and literature references (Ref.) for models to calculate chilling requirements.

Model Name	Description	Ref.
Chilling hours	Simple and widely used. Counts the number of hours below 7.2 °C.	[127]
Utah	Uses temperatures that trees are exposed to, expressed as chilling units (CU): 1 CU for 2.5–9.1 °C, 0.5 CU for 9.2–12.4 °C, 0 CU for <1.4 or 12.5–15.9 °C, –0.5 CU for 16–18 °C, and -1 CU for >18 °C.	[128]
Landsberg	Uses CU based on dividing the daily temperature by a base temperature of the crop. If the base temperature is 5 °C and the daily temperature is 5 °C, then the chilling unit is 1.	[131]
Low Chill	Developed for the low chilling requirements of the ‘Sungold’ nectarine, it can be used for low-chilling-requirement cultivars in subtropics. Uses CU of 1 for 1.8–8 °C, 0 for <–1 and 14–17 °C, and –1 for >19.5 °C.	[132]
North Carolina	Uses CU of 1 for 1.6–7.2 °C, 0 for <–1.1 °C and 16.5–19 °C, and –2 for >23.3 °C.	[133]
Dynamic	Proposes an intermediate product formed in buds due to cold temperature that can be reversed by warm temperature. If this product reaches a certain concentration at cold temperature, the chill portions are permanently fixed, and they are considered unaffected by warm temperature. One chill portion (CP) is an exposure to 6 °C for 28 hours.	[134]
Positive Chill Units (PCU)	A modified version of the Utah model to avoid negative values at warm temperature. CU = 0 is used for >15.9 °C.	[135]
‘Sweetheart’ cherry and ‘Gala’ apple	Uses CU = 1 for –2.1–7 °C (cherry) and –2.1–5.5 °C (apple), –1 for >18 °C (cherry and apple), and 0 for 13–16 °C (cherry and apple).	[136]
Jones I	Was used to study the chilling requirements of 20 blackcurrant genotypes. The model depends on a decreasing exponential curve by fitting a curve with the response to chilling temperature. The decreasing exponential = 1 CU for –2.7 °C, 0.5 CU for 2.0 °C, 0.25 CU for 6.6 °C, and 0.1 CU for 12.8 °C.	[137]
Jones II	Winter chill data of 0–7.2 °C (denoted by 0–7.2 CU) calculated by the summation of total chill hours from October 1st in a relevant year when the mean temperature was 0–7.2 °C. Similarly, <7.2 °C (denoted by 7.2 CU) for mean temperature <7.2 °C, and exponential units (denoted by “exp”), where exp is the summation of hours from 1 October for the function $\text{exp} = 0.6702 [-0.148 \times T_a]$, where T_a is the hourly measured mean temperature.	[138]
Luedeling: ‘chillR’	“chillR” contains functions for processing temperature records into chilling models (chilling hours, Utah, and dynamic models) and heat units (growing degree hours).	[139]

The major three models are the “chilling hours”, “Utah” and “dynamic” models. The chilling hours and Utah models were applied in the temperate regions successfully, but they were less efficient in the Mediterranean and subtropical regions under warm winter conditions [140].

The dynamic model philosophy is dependent upon chilling requirements being determined in two steps started by the accumulation of an intermediate product that is promoted by cold temperature but may be reversed with warmer temperature [134]. The second step includes a certain level of this product that is irreversible even in warm temperature. Therefore, the same temperature should have the same effect using either the chilling hours or Utah model; however, the effect of the same temperature is quite different, since the dynamic model depends on the time the temperature was recorded [60,126]. These three models perform in different ways related to the variability of calculated chilling requirements from one year to another. The dynamic model showed the least variation (0.1–5.9%), followed by the chilling hours model (1.3–9.0%) and the Utah model (2.1–14.0%). Therefore, the dynamic model data were the most preferred to predict winter chill under warm winter conditions [140]. The impacts of climate change in Argentina were studied in vineyards using some bioclimatic indices that characterized the potential climate

changes, which were highly related to the qualitative potential of grapes. Four bioclimatic indices have been used: (i) average growing-season temperature (GST), (ii) cool night index (CNI), (iii) average growing-season precipitation (GSP), and (iv) average monthly minimum temperature (DSTmin) during the dormant season [129]. In Argentina, the viticulture industry may face challenges in warm climate conditions. The cold climate regions in Argentina are favored for grapes either in near- or distant-future production plans, but warm regions have disadvantages for grape production, especially plans in the distant future (i.e., 2075–2099) under climate change scenarios. This means that the warm climate regions may be suitable for current grape cultivar growth or for cultivating new cultivars with fewer chilling requirements [129]. In Morocco, the reduction in chill hours during warm winter resulted in many phenological interruptions such as delayed flowering and/or prolonged flowering period, along with low fruit quality in apple. In seasons when trees had received enough chilling, fruit quality showed better results, especially for fruit weight, size, and firmness. The chilling requirements of apple were 645–677 chill hours using the chilling-hour model, 709–1157 chill units (CU) using the Utah model, and 43.4–55.2 chill portions (CP) using the dynamic model. To maintain adequate apple fruit production in Morocco, the replacement of the current varieties with other varieties that require fewer chilling hours is necessary [29]. Some other findings have also confirmed this conclusion [29,44,130,141–144].

5. Conclusions

As mentioned above, climate change is a generally a great challenge for temperate fruit tree production. The key factors of climate change are the elevated mean temperature and atmospheric CO₂ [1,5]. These changes negatively impact, for instance, the chilling requirements, dormancy, and phenology of temperate fruit trees [127,143,145], especially in growing areas with warm winter conditions where trees cannot fulfill their chilling requirements for dormancy breaking and re-growth by spring. Global warming has led to chill deficit during winter, which may become a limiting factor for growing temperate fruit trees in the tropics and subtropics. Therefore, several dormancy breaking options have been used to compensate chill deficit and induce growth, flowering, and fruiting while maintaining the phenological sequences of the tree. In addition, several models have also been proposed in order to calculate and estimate the required chill conditions in specific regions for temperate fruit tree species and to evaluate the sustainability of a cultivar in a specific region. However, the current status of research on dormancy and chilling under warm winter growing conditions is incomplete, and many scientific problems are unsolved. For example, with the increasing rates of climate change,

- i. New and more effective dormancy breaking organic compounds have to be discovered;
- ii. New climate-smart cultivars have to be bred in order to solve the increasing difficulties for dormancy and chilling requirements [146], i.e., a longer period from the fulfillment of chilling requirements to bud break. This would help to escape spring cold events in some years in Mediterranean areas;
- iii. Dormancy and chilling forecasting models have to be improved further in order to successfully manage temperate fruit tree production worldwide but especially in the tropical and subtropical regions.

If these research issues are successfully addressed in the near future, temperate fruit tree plantations can be protected for a long period, especially in the warm winter regions.

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