Chilling Challenges in a Warming World

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Abstract

Global warming affects perennial horticultural crops in many ways, including potentially by reducing available winter chill. For many fruit and nut species of the temperate and subtropical climates, such as apple, cherry, peach and walnut, fulfilment of cultivar-specific chilling requirements is a prerequisite for breaking dormancy, blooming regularly and ultimately for producing economically satisfactory yields. Global warming may jeopardize the trees' ability to accumulate sufficient winter chill and become fully receptive to spring forcing. In our paper, we review recent evaluations of past and projected future changes in winter chill and discuss implications for the production of temperate fruits and nuts across Europe. Great differences both in historic trends and in future projections were identified when quantifying winter chill with different models. The commonly used Chilling Hours Model is highly sensitive to change due to hard temperature thresholds that are unlikely to be of biological significance. To a slightly lesser degree, this also applies for the Utah Model. Among the evaluated models, only the Dynamic Model instills confidence in its ability to reliably describe the response of winter chill to temperature, but even this model requires more validation. According to the Dynamic Model, changes in winter chill vary across climatic zones, with cold climates (e.g., in Scandinavia) experiencing an increase in winter chill, temperate climates (e.g., central Europe) seeing stagnation and warm growing regions (e.g., southern Europe) facing declining winter chill. In Europe, the warmest growing regions around the Mediterranean Sea are most threatened by reductions in winter chill. Besides highlighting the need to consider projected future climate conditions when selecting tree cultivars, our study stresses the need to improve our understanding of the dormancy-breaking process and to produce and validate quantitatively reliable models for projecting fruit and nut production in a warming world.

INTRODUCTION

Most trees from cold and temperate climates require exposure to cold temperatures during the winter, in order to break dormancy (Saure, 1985; Vegis, 1964). Dormancy protects trees from frost damage in cold winters and preserves nutrients in the woody parts of the tree during the cold season so that growth can quickly resume in spring (Vegis, 1964). Breaking dormancy requires the fulfilment of cultivar-specific chilling and forcing requirements. Once both are met, bloom is initiated and leaves begin to emerge. Regular completion of a tree's annual cycle is only possible, where local climates are able to meet the tree's requirements (Vegis, 1964). Winter chill in particular is a crucial factor in determining a site's suitability for a particular tree species or cultivar. In horticulture, commercial production of temperate tree crops is only possible where specific chilling requirements are met (Rumayor-Rodriguez et al., 1998). For this reason, horticultural researchers have done extensive work on understanding and modeling winter chill

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(Bennett, 1949; Erez et al., 1990; Richardson et al., 1974). According to such models, profit-oriented orchard managers select appropriate cultivars for their production sites.

Climate change threatens to impact winter chill in a way that may disrupt production patterns that have historically been successful (Luedeling et al., 2011a). Most parts of the world have experienced a gradual warming trend over the past century and this trend is projected to continue into the future, possibly at an accelerated pace (IPCC, 2007). In warmer growing conditions, it is likely that winter chill will decrease in many places. This will very likely affect the ability of many growers to maintain traditional production patterns. The high value and long lifespan of perennial fruit tree crops requires adaptation based on considerable foresight about future climate conditions.

This paper reviews the usefulness of current modeling approaches for helping farmers anticipate and respond to changes in winter chill. It also provides an overview of recent efforts to analyze historic and project future trends in winter chill, and of the tools and techniques available to growers for adapting to changes.

WINTER CHILL MODELS

Chilling Hours

The Chilling Hours Model is the oldest of the major models, dating back to the 1940s and developed for peach in the southeastern United States (Bennett, 1949; Weinberger, 1950). This model assumes that each hour, during which temperatures are between 0 and 7.2°C (originally 32 and 45°F) are effective for chill accumulation. Outside this range, temperatures are not effective.

Utah Model

Expanding from the Chilling Hours Model, Richardson et al. (1974) developed the Utah Model, in which the effectiveness of different temperature ranges was varied by a weight function consisting of weightings of 0.5, 1, 0, -0.5 and -1. Negative weights were assigned to temperatures above 15.9°C, which have been shown to negate previously accumulated chilling. Temperatures between 2.4 and 9.1°C received the highest weights. Several authors have modified this model to work in various climatic settings around the world (e.g., Linsley-Noakes and Allan, 1994; Linvill, 1990; Shaltout and Unrath, 1983).

Dynamic Model

The Dynamic Model (Fishman et al., 1987a,b) is the most recent of the common models. It was developed for peach in Israel and it is based on the premise that chill accumulates in a two-step process. The first process, which is most efficient at low temperatures, accumulates an intermediate chill product, which can be destroyed by heat. In the second process, which requires moderate temperature, the intermediate product is converted, in an irreversible process, into a Chill Portion.

Other Approaches

Several other approaches to modeling winter chill have been used or are in use in different growing regions. In addition to variations of the Utah Model, examples include the <7.2°C model (Sunley et al., 2006) and the 0-10°C model (Farag et al., 2010). Several models have also been proposed outside the field of horticulture, but to our knowledge are not used in orchards anywhere (e.g., Chmielewski et al., 2011; Linkosalo et al., 2008). None of these models will be discussed here, but comparative analysis of chill modeling approaches across disciplines might lead to interesting insights in the future.

Model Comparability and Sensitivity to Warming

All of the chill models described above have been used successfully in practical orchard management in many growing regions. All of them have also been used to analyze historic trends in winter chill and to project future changes. Such analyses have often been based on the tacit assumption that a given model is valid for climatic conditions of the past and of the future. Since all models have been based on empirical observations rather than on a thorough understanding of tree physiology, however, this assumption is at least questionable. In fact, studies that have used more than one chilling model have shown that projections and historic trends differed greatly, depending on which model was chosen. Luedeling et al. (2009d) compared climate change effects on modeled winter chill at several locations in California, using four different models exposed to the same climate change scenarios. Chill losses according to the Chilling Hours Model were 2.5 times, and according to the Utah Model 1.5 times greater than those projected according to the Dynamic Model. This finding indicated that choice of the model was the main factor affecting the projections, a result that casts doubts on the suitability of at least two of the models for climate change modeling.

Luedeling and Brown (2011) showed that the ratios between different chilling metrics differ tremendously around the world, based on temperature records from a global dataset of more than 5000 weather stations. For example their analysis showed that the ratio of Chilling Hours to Chill Portions ranged from 0 to 30 and was strongly affected by mean temperature at the site. This means that even at sites with similar amounts of available chill according to a given metric, other models may not classify sites as similar at all. This discrepancy can be problematic, when germplasm is transferred between growing regions.

Several studies have compared chill models, based on theoretical considerations (e.g., Luedeling et al., 2011b; Perez et al., 2008), controlled chilling and forcing experiments (e.g., Ruiz et al., 2007; Zhang and Taylor, 2011) or analysis of phenology time series data (Luedeling et al., 2009e). In most cases, the Dynamic Model was found to be superior to the other approaches, especially in warm growing regions. We are not aware of a study that found advantages for the Chilling Hours Model. The Chilling Hours approach, which is probably most commonly used in orchard management, always performed poorly, and it was much more sensitive to warming than the other major models. This indicates that projections in Chilling Hours are likely to overestimate chill changes due to climate change and misrepresent temperature responses of trees during the winter season. Most authors have therefore recommended use of the Dynamic Model for winter chill analysis across time, space or climate. It should be noted that at least one study in a marginal growing region (the Indian Ocean island of Réunion) has found none of the common models to be useful (Balandier et al., 1993).

HISTORIC AND FUTURE CHILL TRENDS

Historic Changes

Quite a few studies have analyzed historic changes in winter chill, in a number of different geographic contexts. Unfortunately, most of these studies have used units to quantify these changes that are unlikely to be accurate. For example, Wrege et al. (2010; for Brazil), Luedeling et al. (2009b; for mountain oases in Oman) and Baldocchi and Wong (2008; for California) used only Chilling Hours and Farag et al. (2010; for Egypt) used only a model based on temperatures between 0 and 10°C. While these studies probably do not convey quantitatively reliable estimates of historic chill trends, they do give an indication of the direction of change. All these studies showed strongly declining trends in winter chill over the past decades.

These declining trends are confirmed by several studies using models that are likely to be more accurate or using multiple chill models. Midgley and Lötze (2011) found mean chill losses of 26% over 12 weather stations in South Africa between 1967 and 2007 according to a modification of the Utah Model with restricted chill negation (Linsley-Noakes and Allan, 1994). Luedeling et al. (2009c) calculated changes in Safe Winter Chill in California. Safe Winter Chill is the 10% quantile of a stochastic distribution of chill estimates over 100 years. This number represents the maximum chilling requirement of a cultivar that should be exceeded in 90% of all years, probably allowing profitable production. Safe Winter Chill was found to have declined between

1950 and 2000 by between 3 and 6% in different parts of the Central Valley according to the Dynamic Model, compared to 12-23% according to the Chilling Hours concept. Darbyshire et al. (2011) identified declining trends in chill according to four chill models in almost all of 13 sites across southern Australia between 1911 and 2009. Only the coldest locations experienced unchanged conditions or even slight increases according to the Utah and Dynamic Models.

Mixed results were obtained by an analysis by Sunley et al. (2006), who used multiple models for analyzing historic changes in the United Kingdom. Most models showed slight losses, while according to the Utah Model, chill increased slightly. Working in Germany, Luedeling et al. (2009a, 2011b) found no significant changes according to multiple models.

All of the above results were qualitatively confirmed by the only study to date that has analyzed historic chill trends at a global scale (Luedeling et al., 2011a). Comparing Safe Winter Chill between 1975 and 2000, this study found severe losses in warm growing regions and broadly unchanged conditions across the temperate zone. Cold regions were found to have seen increases in winter chill between 1975 and 2000.

Future Projected Changes

Even more than for the historic trends, use of unreliable models can undermine the credibility of future projections. Future projections that are only provided in Chilling Hours (Baldocchi and Wong, 2008; Luedeling et al., 2009b; Wrege et al., 2010) and similar units (Farag et al., 2010) will thus not be discussed further, except as the summary statement that all studies indicated future losses in winter chill that do not bode well for the array of fruit and nut trees currently cultivated at the respective study locations.

Luedeling et al. (2009c) analyzed chill changes for California between 1950 and the middle and end of the 21st century. On average over all parts of the Central Valley, climate scenarios and greenhouse gas emissions scenarios used in the study, they found losses of 19 and 32% for the middle and the end of the 21st century according to the Dynamic Model, and much more severe losses (by 35 and 52%, respectively) for the Chilling Hours Model. For warming scenarios of +0.5, +1.0 and +1.5°C applied to 12 sites in South Africa, Midgley and Lötze (2011) projected losses of 10-30% for cool sites and 10-60% for warm sites according to the Positive Utah Model (Linsley-Noakes and Allan, 1994). Hennessy and Clayton-Greene (1995), using the Modified Utah Model (Linvill, 1990), also projected severe losses for warm sites and moderate losses for cool sites in southern Australia, for uniform warming scenarios by +1, +2 and +3°C, as well as for regionalized outputs of climate models.

Working at a global scale and interpolating over more than 4000 weather stations, Luedeling et al. (2011a) confirmed this general pattern, using the Dynamic Model. For the warmest growing regions, they projected severe losses, which may make cultivation of many traditional fruits and nuts there impossible. As in the analysis of historic trends, temperate regions are projected to be much less affected, and cold regions may even experience an increase in winter chill. Such increases are possible, because freezing temperatures are not considered effective for chill accumulation. Where warming shortens frost periods, increases in chill may thus result.

MODELING FRONTIERS

In spite of considerable efforts that have been expended to develop winter chill models, no currently available model is based on a thorough understanding of the physiological processes involved in chill accumulation. All models are merely empirical proxies of winter chill, and none of them are capable of explaining temperate tree phenology across the full climatic range where such trees are grown. Similarly, confidence in their ability to reliably project future changes is limited, especially in warm growing regions. However, models clearly differ in their credibility, and it appears that the Dynamic Model is currently the front-runner among the common models. Yet most growers do not seem to be aware of these differences, and the arguably least accurate model, the Chilling Hours Model is widely used in fruit and nut production. A transition to the newest – though also no longer particularly new – Dynamic Model would facilitate reliable climate change impact projections and targeted transfer of germplasm with appropriate chilling requirements for future climates. In the long run, however, a quantitative and physiological understanding of dormancy-breaking processes should be a priority goal for horticultural research. This will be needed for developing a process-based model, which could then be used to project climate change impacts. Systematic experimentation will probably be necessary to gain new insights into chill accumulation.

Statistical analysis of long-term phenology data may also generate new knowledge. Luedeling and Gassner (2012) have recently used Partial Least Squares (PLS) regression to analyze walnut phenology in California. Unlike most other regression methods, this type of analysis allows distinguishing between the effects of temperature anomalies at different times during the winter on spring phases of trees. The authors were able to show when chill and heat accumulate, and they identified quantitative differences in the effectiveness of chill throughout the season, which are currently not included in any chill models. Their results, as well as findings for grasslands on the Tibetan Plateau (Yu et al., 2010) have shown that winter warming, contrary to what many might expect, can have a delaying effect on spring phases of temperate and cold-climate plants. Horticulturalists should also consider the idea that chilling and heat requirements are not fixed, but may vary from year to year. According to results by Harrington et al. (2010), insufficient chill may even be compensated by more heat, so that bloom is possible at different combinations of chill and heat.

Other areas that horticultural chill models do not currently include are potential effects of dormancy induction conditions on chilling requirements, as well as effects of day length or the ratio of red/far red radiation, which may help explain some of the variation in bloom dates that chill and heat models alone have so far not been able to explain. For progress towards more biologically complete tree dormancy models, systematic research is needed on the various factors that may influence buds during the dormancy season. This will require either controlled environment studies or standardized collection of phenology data across a range of environments.

IMPLICATIONS FOR GROWING TEMPERATE FRUITS AND NUTS

Selecting appropriate germplasm based on reliable models would probably be the most effective adaptation strategy. Along the same lines, breeding for low chilling requirements should be intensified. Yet even when chilling requirements are not quite met, some tools are available to growers for alleviating the most immediate effects of insufficient chill. Microclimate manipulation in orchards, by overhead irrigation (Erez, 1995) or shading (Campoy et al., 2010) has shown some positive results, when applied at the right time. In tropical regions, where essentially no chill is available, artificial defoliation has been used to induce a kind of dormancy that does not require chill (Edwards, 1987). While this strategy would certainly not work in cooler areas, where dormancy is required for averting frost damage, studying the underlying mechanisms could lead to interesting new insights. In many growing regions, chemical rest-breaking agents are increasingly being used to not only break dormancy, but also to ensure regular and homogeneous bloom. Examples of such agents are hydrogen cyanamide (Ashebir et al., 2010), thidiazuron (Campoy et al., 2010) and certain nitrogen compounds (de Salvador and di Tommaso, 2003).

Trends in winter chill in many growing regions indicate that growers of temperate tree crops should begin to include climate change considerations into their planning process. They should use adequate metrics to monitor chill, plan their cultivar selection to ensure that trees will stay adapted throughout their productive life time, and they should familiarize themselves with options to compensate for lack of chill. Climate change is particularly problematic for those who did not see its impacts coming and who are not adequately prepared. If climate change becomes a major factor in the planning of orchard operations, growers may be able to avert the worst consequences of global warming.

Literature Cited

Ashebir, D. et al. 2010. Growing apple (*Malus domestica*) under tropical mountain climate conditions in northern Ethiopia. Exp. Agric. 46(1):53-65.

Balandier, P., Bonhomme, M., Rageau, R., Capitan, F. and Parisot, E. 1993. Leaf bud endodormancy release in peach-trees – evaluation of temperature models in temperate and tropical climates. Agric. For. Meteorol. 67(1-2):95-113.

Baldocchi, D. and Wong, S. 2008. Accumulated winter chill is decreasing in the fruit growing regions of California. Climatic Change 87:S153-S166.

Bennett, J.P. 1949. Temperature and bud rest period. Calif. Agric. 3(11):9, 12.

Campoy, J.A., Ruiz, D. and Egea, J. 2010. Effects of shading and thidiazuron + oil treatment on dormancy breaking, blooming and fruit set in apricot in a warm-winter climate. Sci. Hort. 125(3):203-210.

Chmielewski, F.M. et al. 2011. Phenological models for the beginning of apple blossom in Germany. Meteorol. Z. 20(5):487-496.

Darbyshire, R., Webb, L., Goodwin, I. and Barlow, S. 2011. Winter chilling trends for deciduous fruit trees in Australia. Agric. For. Meteorol. 151(8):1074-1085.

de Salvador, F.R. and di Tommaso, G. 2003. Dormancy control in cherry. Inform. Agr. 59(45):63-66.

Edwards, G.R. 1987. Producing temperate-zone fruit at low latitudes - avoiding rest and the chilling requirement. HortScience 22(6):1236-1240.

Erez, A. 1995. Means to compensate for insufficient chilling to improve bloom and leafing. Acta Hortic. 395:81-95.

Erez, A., Fishman, S., Linsley-Noakes, G.C. and Allan, P. 1990. The dynamic model for rest completion in peach buds. Acta Hortic. 276:165-174.

Farag, A.A., Khalil, A.A. and Hassanein, M.K. 2010. Chilling requirement for deciduous fruits under climate change in Egypt. Res. J. Agr. Biol. Sci. 6(6):815-822.

Fishman, S., Erez, A. and Couvillon, G.A. 1987a. The temperature-dependence of dormancy breaking in plants – computer-simulation of processes studied under controlled temperatures. J. Theor. Biol. 126(3):309-321.

Fishman, S., Erez, A. and Couvillon, G.A. 1987b. the temperature dependence of dormancy breaking in plants: mathematical analysis of a two-step model involving a cooperative transition. J. Theor. Biol. 124(4):473-483.

Harrington, C.A., Gould, P.J. and St.Clair, J.B. 2010. Modeling the effects of winter environment on dormancy release of Douglas-fir. For. Ecol. Manage. 259(4):798-808.

Hennessy, K.J. and Clayton-Greene, K. 1995. Greenhouse warming and vernalization of high-chill fruit in southern Australia. Climatic Change 30(3):327-348.

IPCC. 2007. Climate Change 2007 - Synthesis Report. Contributions of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Intergovernmental Panel on Climate Change, Geneva, Switzerland.

Linkosalo, T., Lappalainen, H.K. and Hari, P. 2008. A comparison of phenological models of leaf bud burst and flowering of boreal trees using independent observations. Tree Physiol. 28(12):1873-1882.

Linsley-Noakes, G.C. and Allan, P. 1994. Comparison of 2 models for the prediction of rest completion in peaches. Sci. Hort. 59(2):107-113.

Linvill, D.E. 1990. Calculating chilling hours and chill units from daily maximum and minimum temperature observations. HortScience 25(1):14-16.

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

Luedeling, E. and Brown, P.H. 2011. A global analysis of the comparability of winter chill models for fruit and nut trees. Int. J. Biometeorol. 55(3):411-421.

Luedeling, E. and Gassner, A. 2012. Partial least squares regression for analyzing walnut phenology in California. Agric. For. Meteorol. 158:43-52.

Luedeling, E., Gebauer, J. and Buerkert, A. 2009b. Climate change effects on winter chill for tree crops with chilling requirements on the Arabian Peninsula. Climatic Change 96:219-237.
Luedeling, E., Girvetz, E.H., Semenov, M.A. and Brown, P.H. 2011a. Climate change affects winter chill for temperate fruit and nut trees. PLoS ONE 6(5).
Luedeling, E., Kunz, A. and Blanke, M. 2011b. More winter chill for fruit trees in warmer winters? - Mehr Chilling für Obstbäume in wärmeren Wintern? Erwerbs-Obstbau 53(4):145-155.
Luedeling, E., Zhang, M. and Girvetz, E.H. 2009c. Climatic changes lead to declining winter chill for fruit and nut trees in California during 1950-2099. PLoS ONE 4(7):e6166.
Luedeling, E., Zhang, M., Luedeling, V. and Girvetz, E.H. 2009d. Sensitivity of winter chill models for fruit and nut trees to climate change. Agric. Ecosyst. Environ. 133:23-31.
Luedeling, E., Zhang, M., McGranahan, G. and Leslie, C. 2009e. Validation of winter chill models using historic records of walnut phenology. Agric. For. Meteorol. 149:1854-1864.
Midgley, S.J.E. and Lötze, E. 2011. Climate change in the western cape of South Africa: trends, projections and implications for chill unit accumulation. Acta Hortic. 903:1127-1134.
Perez, F.J., Ormeno N.J., Reynaert, B. and Rubio, S. 2008. Use of the dynamic model for the assessment of winter chilling in a temperate and a subtropical climatic zone of Chile. Chil. J. Agr. Res. 68:198-206.
Richardson, E.A., Seeley, S.D. and Walker, D.R. 1974. A model for estimating the completion of rest for Redhaven and Elberta peach trees. HortScience 9(4):331-332.
Ruiz, D., Campoy, J.A. and Egea, J. 2007. Chilling and heat requirements of apricot cultivars for flowering. Environ. Exp. Bot. 61:254-263.
Rumayor-Rodriguez, A., Zegbe, J.A. and Medina-Garcia, G. 1998. Use of a geographical information system (GIS) to describe suitable production areas for peach. Acta Hortic. 465:549-556.
Saure, M.C. 1985. Dormancy release in deciduous fruit trees. Hortic. Rev. 7:239-300.
Shaltout, A.D. and Unrath, C.R. 1983. Rest completion prediction model for Starkrimson Delicious apples. J. Am. Soc. Hortic. Sci. 108(6):957-961.
Sunley, R.J., Atkinson, C.J. and Jones, H.G. 2006. Chill unit models and recent changes in the occurrence of Winter chill and Spring frost in the United Kingdom. J. Hortic. Sci. Biotech. 81(6):949-958.
Vegis, A. 1964. Dormancy in higher plants. Annual Review of Plant Physiology 15:185-224.
Weinberger, J.H. 1950. Chilling Requirements of Peach Varieties. P. Am. Soc. Hortic. Sci. 56(DEC):122-128.
Wrege, M.S. et al., 2010. Impact of global warming on the accumulated chilling hours in the Southern Region of Brazil. Acta Hortic. 872:31-40.
Yu, H., Luedeling, E. and Xu, J. 2010. Winter and spring warming result in delayed spring phenology on the Tibetan Plateau. Proc. Nat. Acad. Sci. USA 107(51):22151-22156.
Zhang, J. and Taylor, C. 2011. The dynamic model provides the best description of the chill process on 'Sirora' pistachio trees in Australia. HortScience 46(3):420-425.