Using Thermal Time to Simulate Dormancy Depth and Bud-Burst of Vineyards in Korea for the Twentieth Century

EUN-YOUNG KWON, JEA-EUN JUNG, URAN CHUNG, AND JIN I. YUN
Department of Ecosystem Engineering, Kyung Hee University, Suwon, Korea

HEE-SEUNG PARK
Department of Applied Plant Science, Chung-Ang University, Anseong, Korea

ABSTRACT
A winter-season warming trend has been observed in eastern Asian countries during the last century. Significant effects on dormancy and the subsequent bud-burst of deciduous fruit trees are expected. However, phenological observations are scant in comparison with long-time climate records in the region. Chill-day accumulation, estimated from daily maximum and minimum temperature, is a reasonable proxy for dormancy depth of temperate-zone fruit trees. A selected chill-day model was parameterized for the Campbell Early grapevine, which is the major cultivar (grown virtually everywhere) in South Korea. To derive model parameters (threshold temperature for chilling and the chilling requirement for breaking dormancy), a controlled-environment experiment using field-sampled twigs of Campbell Early was conducted. The chill-day model to estimate bud-burst dates was adjusted by derived parameters and was applied using 1994–2004 daily temperature data obtained from the automated weather station in the vineyard at the National Horticultural Research Institute. The model gave consistently good performance in predicting bud-burst of Campbell Early (RMSE of 2.5 days). To simulate dormancy depth of Campbell Early at eight locations in South Korea for the last century, the model was applied using data obtained for each location from 1921 to 2004. Calculations showed that the chilling requirement for breaking endodormancy of Campbell Early can be satisfied by mid-January to late February in South Korea, and the date was delayed going either northward or southward from the Daegu–Jeonju line that crosses the middle of South Korea in the east–west direction. Maximum length of the cold tolerant period (the number of days between endodormancy release and the forced dormancy release) showed the same spatial pattern. Dormancy release for 1981–2004 advanced by as much as 15 days relative to that for 1921–50 at all locations except Jeju (located in the southernmost island with a subtropical climate), where an average 15-day delay was predicted. The cold-tolerant period diminished somewhat at six out of eight locations. As a result, bud-burst of Campbell Early in spring was advanced by 6–10 days at most locations, and interannual variation in bud-burst dates increased at all locations. The earlier bud-burst after the 1970s was due to 1) warming in winter that results in earlier dormancy release (Incheon, Mokpo, Gangneung, and Jeonju), 2) warming in early spring that enhances regrowth after breaking dormancy (Busan and Jeju), and 3) a combination of both (Seoul and Daegu).

1. Introduction
One of the most remarkable features of global change in eastern Asian countries is the warming in the winter–early spring season and the resultant modulation of plant phenology (Piao et al. 2006; Doi 2007). For the recent 50 yr (1951–2000), January–March mean temperature increased by up to 1.0°C, whereas the increase in July–September mean temperature was less than 0.4°C in South Korea (Chung et al. 2004). Earlier spring flowering was consequently observed for several deciduous tree species, including golden-bell (Forsythia koreana), azalea (Rhododendron mucronulatum), Japanese cherry (Prunus serrulata), and American locust (Robinia pseudoacacia). For these wild species, routine phenological observations were made at major synoptic stations by the Korea Meteorological Administration (KMA). The KMA uses an empirically based method
to issue blooming-date forecasts across the nation to help authorities to schedule spring flower festivals. The importance of this service is growing because of climatic-change-induced weather episodes and resultant erratic flowering dates, which might spoil the spring flower festivals.

Although deciduous fruit trees such as pear, apple, peach, and grape are important cash crops for farmers in South Korea, no observed data for spring phenology of these fruit trees are available on a routine basis. Hence, there is no flowering-date forecast by the KMA. Flowering of temperate deciduous trees in spring is a visible result of a series of physiological processes across seasons. Therefore, any change in flowering date implies change in these processes, though invisible, during winter and spring. Dormancy is one of the most interesting processes, not only to plant physiologists but also to farmers of deciduous fruit trees who must make decisions with respect to plant cold injury. Plant cold hardiness depends, to some extent, on the degree of acclimation to low temperature and may be estimated quantitatively by the depth of dormancy (Kwon et al. 2006). Farmers growing fruits under plastic-film shelters in winter must decide whether to begin heating to advance bud-burst. They know the optimal time for heating should be at the date when plants are released from dormancy. However, methods have not yet been developed to measure dormancy depth directly or to detect dormancy release without destroying tissues or cells.

Instead of direct measurement of dormancy depth, “dormancy clock” models driven by temperature data have been used to estimate dormancy depth indirectly and to determine the dormancy release date. Under natural conditions, plants must be chilled with appropriate low temperature for a long enough period to be released from dormancy, and this amount (chilling requirement) may be expressed as a specific weighted sum of hourly temperature (Seeley 1996). Chilling requirement is usually quantified by thermal time, which is a combination of clock time and temperature. The heating requirement is based on the minimum amount of time to bud-burst after the date of dormancy release. Dormancy-clock models have been modified to accommodate daily temperature data instead of hourly data and have been successfully used to predict bud-burst and flowering in many subtropical tree species (Cesaraccio et al. 2004; De Melo-Abreu et al. 2004) and temperate deciduous trees (Jung et al. 2005; Kwon et al. 2006).

During recent decades, grape has been one of the most important fruits in South Korea, with the second- or third-highest rankings in both national consumption and production. The “Campbell Early” grape was introduced to South Korea in 1908 and has been continuously grown since, has nationwide acreage, and has become the most popular variety. Because daily temperature data at several locations in South Korea are available for this period, we may estimate the winter-season phenology of Campbell Early for the past century using a dormancy-clock model. The implied (or estimated) phenology may tell us the impact of climatic change on one of the most important fruit species in South Korea, and derived information could be used to develop an adaptation strategy for fruit growers to project climatic-change impacts in this region.

The objectives of this study are 1) to parameterize an existing phenology model for accurate simulation of the dormancy status of the Campbell Early grapevine cultivar, 2) to estimate the dormancy-status data for Campbell Early in the 1921–2004 period by use of this model and observed temperature data, and 3) to determine changes in the winter–spring phenology of vineyards in South Korea during the past century.

2. Materials and methods

a. Overview

A thermal time–based two-step phenological model described by Cesaraccio et al. (2004) was parameterized for Campbell Early. To derive the model parameters (threshold temperature for chilling and the chill requirement for breaking of dormancy), a controlled-environment experiment using field-sampled twigs of Campbell Early was conducted at the National Horticultural Research Institute (NHRI) from November 2004 to February 2005. The model, adjusted by selected parameters, was applied to the 1994–2004 daily temperature data obtained from the automated weather station in the NHRI vineyard to estimate bud-burst dates, and the results were compared with the observed data. To simulate dormancy depth of Campbell Early during 1921–2004, the model was applied to the relevant temperature data at eight locations in South Korea.

b. Model

Dormancy consists of two sequential periods according to Cesaraccio et al. (2004): a rest period described by the chill requirement and a quiescent period described by the heat-accumulation requirement. The number of days from dormancy to bud-burst is predicted by sequential accumulation of chill units for the rest period and heat units for the quiescent period. In our model, the quiescent period is subdivided at the
date of forced dormancy release into a so-called environmental dormancy period and a physiological activation period. The environmental dormancy period is defined as no heat-unit accumulation in normal years and includes the period of maximum chill-day accumulation. We may expect plants to show the greatest cold resistance during this period. The physiological activation period starts when daily temperature rises high enough to accumulate positive heat units. Phasic development increases with daily warming, and cold tolerance diminishes during this period. Bud-burst is assumed to take place when accumulated chill days are counteracted by accumulated antichill days.

In the model, daily maximum and minimum temperatures are used to calculate daily chill units until the predetermined chill requirement for rest release is met. After the projected rest-release date, daily heat units (growing-degree-days) are accumulated until the predetermined heat-accumulation requirement for flowering is achieved (Fig. 1). This model requires three parameters that should be determined beforehand by users: the starting date of bud dormancy, the chill requirement for rest release, and the heat requirement for flowering. The heat requirement for bud-burst is assumed to be the same as the chill requirement for rest release with the opposite sign (Cesaraccio et al. 2004). If the temperature threshold is not known, users may also develop site-specific temperature thresholds $T_c$, in addition to chill requirements $C_R$ and heat requirements $C_h$ by species using a long-term dataset of daily temperature and phenology observations.

c. Derivation of model parameters for Campbell Early

Controlled-environment experiments using field-sampled twigs of Campbell Early cultivar were carried out in the vineyard at the NHRI in Suwon during 2004-05 to derive the model parameters: threshold temperature for chilling and chilling requirement for breaking endodormancy.

One hundred cuttings were prepared from 10 twigs collected at random from the NHRI vineyard on 1 December 2004. The twigs were cut into segments bearing three nodes per segment, with the uppermost one 1 cm from the apical tip and the lowest one 4–5 cm from the basal tip. Ninety segments were put into a thermally insulated chamber at $3^\circ$C in the dark while the remaining 10 segments were put into another chamber at $25^\circ$C under $12/24$-h photoperiod using fluorescent lamps. The basal tip was soaked in water, and the cut surface was coated with an antifungal sealant (thiophanate-methyl, the commercial name of which is Topsin). A temperature of $3^\circ$C allows the endodormancy release but prevents the growth of buds if endodormancy has already been achieved (Balandier et al. 1993). At 7-day intervals, 10 cuttings were moved from the $3^\circ$C chamber to the $25^\circ$C chamber and bud-burst observations for each axillary leaf bud were made at 1000 LT each day. Bud-burst was assumed when a green tip was seen between the swollen bud scales. We calculated the arithmetic mean time to bud-burst since moving from the $3^\circ$C chamber and plotted it on a graph with the moving date as $x$ axis. The lapsed days to bud-burst, initially large in number, decreased rapidly and stabilized at a certain number. The results were graphed, and inspection was used to identify the minimum number of days required for bud-burst after endodormancy release.

Beginning on 29 December 2004, 10 cuttings were prepared every week from the NHRI vineyard through the same procedure as the previous experiment. They were put into a chamber at $25^\circ$C and bud-burst was observed at 1000 LT each day. Observation was made on three buds per cutting, and the mean and the standard deviation for the 30 observations were calculated. When the calculated mean reached the minimum number of days for bud-burst, endodormancy was assumed to be released.

Temperature data were collected from an automated weather station installed in the vineyard and were used to calculate chill-days accumulation using four different base temperatures ($6^\circ$, $7^\circ$, $8^\circ$, and $9^\circ$C) and the empirical formulation suggested by Cesaraccio et al. (2004; Table 1). The chill-day accumulation continued until it was equal to the dormancy release requirement deter-
d. Model run

The model was run with daily temperature data at eight locations in South Korea to simulate the time course of dormancy depth for Campbell Early cultivar expressed in chill days during 1921–2004 (Fig. 2). Long-term climate records during 1971–2000 show that Jeju, the southernmost location, can be characterized as subtropical climate with the mean temperature of 5.6°C, minimum 3.0°C, and maximum 8.3°C for the coldest month (January). Incheon and Seoul, the northernmost locations, can be characterized as a temperate climate with a mean temperature of −2.5°C, minimum −6.1°C, and maximum 1.6°C for the coldest month (January).

Starting on 1 October each year, daily chill days were calculated by the model based on daily maximum and minimum temperature data, and daily chill days were accumulated until the predetermined \( R_c \) was met. From this date on (i.e., endodormancy release), the so-called environmental dormancy starts. It is expected that cold weather will prevent accumulation of heat units in most of South Korea during this interval. Environmental dormancy is assumed to be released when a positive heat-unit value begins to accumulate. If daily heat units (antichill days) accumulate and reach the predetermined heating requirement (the same as chilling requirement with the opposite sign), bud-burst is expected to take place on that date. Daily maximum and minimum temperatures were also used to calculate daily heat units during 1921–2004 by the model.

3. Results and discussion

a. Model parameters and validity of the model

The number of days required for sufficiently chilled buds of Campbell Early to reach bud-burst was estimated as 19 ± 2.2 days according to the chamber experiment. Based on this result, chilling requirements for Campbell Early were calculated for four different base temperatures, resulting in \( R_c \) values of −102, −127, −151, and −178 for \( T_c \) values of 6°C, 7°C, 8°C, and 9°C, respectively. When we used these values to predict bud-burst of the NHRI vineyard in 1994–2004, the best result was obtained from the combination of \( T_c = 8°C \) and \( R_c = −151 \) with 2.51 days of RMSE (Fig. 3).

b. Characteristics of dormancy

We calculated chill days from daily temperature data and accumulated them daily at eight locations during 1921–2004. Time-course change in annual dormancy depth at each location is plotted, and the 83 lines can be superimposed in a single plot for comparison (Fig. 4). In general, the maximum dormancy depth (−151 in chill days) is maintained for a period of time at all locations. Chill days are accumulated when daily minimum temperature falls below 8°C, and antichill days do not accumulate until daily maximum temperature rises to 8°C. Therefore, warmer locations show slow start of dormancy but fast fulfilling of chill requirement, resulting in earlier bud-burst. Locations in the northernmost cooler region show an earlier start of dormancy but very slow and more erratic accumulation of chill days, resulting in late bud-burst. Locations that are between show an early start of dormancy, slow but predictable accumulation of chill days, and longer duration of forced dormancy.

The curve pattern may be grouped into three types based on similarity: late start of endodormancy and forced dormancy.
short duration of environmental dormancy (type V; Jeju, Busan, and Mokpo), early start of endodormancy and longer duration of environmental dormancy (type U; Gangneung, Daegu, and Jeonju), and early start of endodormancy but erratic accumulation of chill days (type W; Incheon and Seoul).

Although rest-release date varies considerably from mid-January in Daegu to late February in Incheon, there seems to be some regularity in geographical deviation (Table 2 and Fig. 2). Rest release starts from the Daegu–Jeonju line that crosses the middle of South Korea and spreads out both in the north and south directions, resulting in very similar rest-release dates for geographical locations far from each other (e.g., northernmost Incheon and southernmost Jeju). When we subtract the endodormancy release date from the environmental dormancy release date, the resulting period can be considered as “cold resistant.” There is a clear distinction in the duration of the cold-resistant period between warm and cold regions separated by the Daegu–Jeonju line (Fig. 2). In terms of climate, we can expect that Campbell Early experiences cold tolerance longer if grown north of the Daegu–Jeonju line than if grown in the south. Hence, the Daegu–Jeonju line seems to be a transition zone in plant phenology as well as in climatic features. In relation to the timing of rest release and bud-burst, the Daegu–Jeonju line is also considered to be an optimal place for growing Campbell Early in Korea with respect to prevention of freezing and frost injury.

c. Climatic-change impacts

1) DORMANCY DEPTH

When the 1981–2004 average dates for dormancy release are compared with those for 1921–50, earlier release is found at six out of eight locations and delayed release is found in two locations, though the statistical significance was variable among the locations (Fig. 5a). Dormancy release was advanced by as much as 15 days (in Mokpo), but delayed by 15 days in Jeju, an island with mild climate. This result indicates that recent warming trends in South Korea affected winter phenology of Campbell Early in contrasting ways, depending
on the geographic location. Considering that daily temperatures below zero contribute no chill days and most inland locations show minimum temperatures slightly below zero ranging from $-0.3^\circ$C (Busan) to $-6.1^\circ$C (Seoul) in January, the reported winter warming of $1^\circ$–$2^\circ$C for the last century has definitely made a positive effect on chill-day accumulations in inland locations. In Jeju, where January temperatures range from $3^\circ$C (daily minimum) to $16^\circ$C (daily maximum), chill-day accumulations must have been retarded by further warming.

Annual variation (standard deviation) in dormancy release showed the same tendency as the mean increase in Jeju but reduction in the remaining inland locations (Fig. 5d). However, the magnitude of reduction was in
the opposite pattern: larger variation with smaller reduction. For example, Incheon showed a big reduction in dormancy release during the last century, but annual variation has changed very little. Seoul showed a big change in annual variation but little change in dormancy release date during the same period. This trend indicates that stabilization of dormancy release date could be possible by warming-induced advancement of dormancy release in colder regions.

Forced dormancy release showed a similar pattern to endodormancy release. For example, Incheon showed a big reduction in dormancy release during the last century, but annual variation has changed very little. Seoul showed a big change in annual variation but little change in dormancy release date during the same period. This trend indicates that stabilization of dormancy release date could be possible by warming-induced advancement of dormancy release in colder regions.

### Table 2. Endodormancy release date, forced dormancy release date, and duration of maximum cold tolerance of Campbell Early grapevine at the eight locations in South Korea averaged for 1921–2004.

<table>
<thead>
<tr>
<th>Site</th>
<th>Endodormancy release (day of year)</th>
<th>Forced dormancy release (day of year)</th>
<th>Cold-tolerant period (days)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean</td>
<td>Std dev</td>
<td>Mean</td>
</tr>
<tr>
<td>Incheon</td>
<td>57.9</td>
<td>19.7</td>
<td>63.4</td>
</tr>
<tr>
<td>Seoul</td>
<td>48.4</td>
<td>23.3</td>
<td>57.2</td>
</tr>
<tr>
<td>Gangneung</td>
<td>27.4</td>
<td>16.7</td>
<td>35.8</td>
</tr>
<tr>
<td>Daegu</td>
<td>14.5</td>
<td>19.0</td>
<td>19.9</td>
</tr>
<tr>
<td>Jeonju</td>
<td>19.4</td>
<td>21.3</td>
<td>27.7</td>
</tr>
<tr>
<td>Mokpo</td>
<td>30.3</td>
<td>14.0</td>
<td>33.7</td>
</tr>
<tr>
<td>Busan</td>
<td>34.3</td>
<td>10.6</td>
<td>37.4</td>
</tr>
<tr>
<td>Jeju</td>
<td>52.6</td>
<td>10.6</td>
<td>55.3</td>
</tr>
</tbody>
</table>

**Fig. 5.** Changes in (a) endodormancy release date, (b) forced dormancy release date, (c) maximum cold tolerance duration, (d) std dev of endodormancy release date, (e) std dev of forced dormancy release date, and (f) std dev of cold tolerance duration of Campbell Early at eight weather stations between 1921–50 and 1981–2004. Vertical lines represent the least significant difference (LSD) between two periods at $\alpha = 0.05$ level.
that of endodormancy (Figs. 5b,e). Because we hypothesized that the duration of maximum tolerance to cold would be the period between endodormancy release and forced dormancy release, any change in both dates should also result in change in duration of maximum tolerance. The duration was, in general, shortened, with a maximum reduction of 5 days at Seoul and Gangneung; however, Incheon showed a slight expansion (Fig. 5c). Annual variation also showed a reduction pattern similar to the mean (Fig. 5f).

2) Bud-burst

Bud-burst takes place as a sequential reaction of plants to chilling temperature for dormancy in winter and to heating temperature for growth of primordia in spring. Bud-burst dates of Campbell Early simulated by the model show a long-term advancing tendency together with an increased interannual variation (Fig. 6). The advancement seemed to begin in the 1970s. For readability, results from only two locations, Busan and Incheon, are displayed in Fig. 6, but the other cases are all located between these two extremes. The model calculation for Jeju, the warmest site, follows nearly the same pattern as that of Busan during the first 50 yr but deviates from this pattern in the recent 30 yr, showing no advancement of bud-burst and occasional failures caused by insufficient chilling (Fig. 4). Occasions of abnormal flowering in Jeju have recently been observed, and winter warming is assumed to be one of the major causes [S.-J. Jeon, National Institute for Subtropical Agriculture (Jeju), 2006, personal communication (http://www.nisa.go.kr/)].

We divided the period into segments (1921–50, 1951–80, and 1981–2004) and plotted the average date of bud-burst, and the duration between dormancy release and bud-burst for each segment (Fig. 7a). Although there was a large variation in dormancy release date among locations (Table 2), much less variation exists in bud-burst date. Those locations favoring earlier dormancy release tend to experience extended cold weather in winter or early spring, whereas the other locations favoring delayed dormancy tend to experience the more rapid warming. Because bud-burst after dormancy release is retarded by cold temperature and advanced by warm temperature, the geographical variation in dormancy release date will be compensated for by the opposite pattern of temperature. The average number of days to bud-burst after dormancy release was about 80 days in Daegu and Jeonju with earlier release of endodormancy and was 60 days in Seoul and Incheon with late release of endodormancy (Fig. 7b). In Jeju, where winter warming has greatly retarded dormancy release, the duration between dormancy release and bud-burst was reduced to 45 days.

We calculated the bud-burst date difference between the averages for 1921–50 and 1981–2004 to quantify the potential effects of climate change. Advancement in bud-burst by 6–10 days is common in all locations except in Jeju, where an earlier bud-burst of less than 2 days was calculated (Fig. 8a). When we evaluated, in
like manner, the number of days required for bud-burst after rest release, much more variation was found. There was a 15-day reduction in Jeju; a 3–5-day increase in Incheon and Mokpo; a 3–5-day reduction in Seoul, Daegu, and Busan; and little change was found in the other locations (Fig. 8b). Delayed rest release forced the flowering bud in Jeju to encounter a much warmer period for the heating process and resulted in a much shorter duration for bud-burst. In Mokpo and Incheon, rest release was much earlier than before and flowering buds encountered low temperature, resulting in delayed bud-burst. Interannual variation in bud-burst date increased at all locations, and the standard deviation varied from less than 1 to slightly more than 2 days (Fig. 6c). Although the increase in annual variation seems very small in Jeju, the actual variation is much larger, considering the no-bud-burst cases caused by insufficient chilling for rest release.

4. Conclusions

The phenology–climate connections have several implications. Where there is no observed temperature data, spring phenological phases serve as proxy data for spring air temperature (Menzel 2002). If there are no phenological observations available, temperature data might be used to estimate them. In addition, an accurate description of the phenology–climate relationship is a prerequisite to studying the impacts of climate change. The predicted responses of plants and animals may be useful for allowing society to prepare countermeasures to climate change and to adapt agricultural systems to future climates.
The most striking feature of climate change in eastern Asian countries during the past century may be the remarkable winter-season warming. We expect significant impact on winter dormancy and on the resulting spring bud-burst for crops and fruit trees as well as for the natural vegetation in this region, much as has been observed in Europe (Chmielewski et al. 2004). However, routine phenological observations are rare, and the data are insufficient when compared with the long records of climate observations in this region.

We have introduced a simple way to use an existing phenology model to estimate winter dormancy and spring bud-burst for a grape cultivar based on observed temperature data. According to our calculations, we may conclude that regional warming in South Korea during the past century advanced not only the release date of endodormancy in Campbell Early but also the release date of forced dormancy, resulting in shorter duration of physiological tolerance of plants to cold winter weather and consequent increased vulnerability to freeze and frost events.

One of the next steps in relation to this study should be preparation of temperature data grids with spatial resolution high enough to describe local climates relevant to the local agricultural and forest management systems. We may potentially apply the same method to landscape scale or even to field scale for issuing of decision-aid information in site-specific farming. For example, most freeze forecasting systems employ only daily minimum temperature for judging the potential damage on dormant flowering buds but cannot accommodate any effects from abrupt changes and annual variation in the local climate. Dormancy depth can be used as a complementary criterion for judging the potential damage of freezing temperatures on dormant flowering buds of grapevines in addition to the daily minimum temperature (Faust 1989; Kwon et al. 2006). Daily accumulation of thermal time to predict the dormancy depth for today and the minimum temperature forecasts for tomorrow morning can potentially be used to predict freeze risk and damage probability as appropriate freeze risk models are developed.

Acknowledgments. This work was funded by the Korea Meteorological Administration Research and Development Program under Grant CATER 2006-4502. We are grateful to Gi-Cheol Song of the National Horticultural Research Institute for providing facilities and technical assistance. The insightful comments of the anonymous reviewers greatly improved the paper.

REFERENCES


