

Comparing Heat Unit Accumulation and Fruit Development Period in Peach Breeding Material from Clemson University

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Abstract

Anticipating fruit maturation is critical for peach growers' orchard management and marketing. Due to short shelf life and the perishable nature of peach fruit, peach growers grow many cultivars in a season to provide continuous supply of fresh fruit to consumers. To efficiently manage orchard operations, peach growers use a heat unit model (growing degree hours [GDH] or days [GDD]), to predict peach fruit maturity and aid in harvest scheduling. Heat unit model calculates accumulated heat and relates it to key physiological stages, such as ripening time, in a plant life cycle. Ripening time of peach cultivars is reported as calendar date, day-of-year, number of days from full bloom to ripening, e.g. fruit development period (FDP), or as the number of days before or after a reference cultivar. Presenting ripening time this way does not account for seasonal variation and is not adaptable to climate change. To determine which of these approaches are the most accurate and least variable in predicting ripening time, we compared heat unit accumulation (GDD/GDH) with FDP in 97 peach and nectarine accessions from the Clemson University peach breeding program over six growing seasons (2018-2023). The observed variability and its implication for enabling ripening predictions to producers and researchers, as well as for application in breeding programs and cultivar development are discussed.

Ability to predict ripening is an important step in orchard management for scheduling harvest times, coordinating labor, pest management, and various other purposes. South Carolina peach growers grow on average over 50 peach cultivars in the season and are using a harvest prediction model (Grossman and DeJong 1994; Mimoun and DeJong 1999) based on Growing Degree Days (GDD) or Growing Degree Hours (GDH) to estimate ripening time and manage harvest in their orchards. GDD/GDH model utilizes weather information to calculate the accumulation of heat units above a specific baseline

temperature, which can track different growth stages, such as ripening, of peach cultivars (Day et al. 2008; Kenealy et al. 2015; Verma et al. 2023). Ripening time of peach cultivars is reported as the calendar day, day-of-year (DOY; sometime referred to as Julian Date), or as the number of days before or after a reference cultivar. Unlike calendar day or DOY, which do not account for temperature variations, GDD/GDHs provide a more precise measurement that adapts to the actual growing conditions, making them particularly useful in the context of climate variability and change. Fruit development period (FDP) is another

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option that reports ripening time as the number of days between the full bloom and ripening but is rarely provided. Studies investigating heat accumulation for bloom (Atagul et al. 2022) or ripening (Kenealy et al. 2015; Day et al. 2008) showed seasonal variability in GDH and GDD accumulation 30 days after full bloom (GDH30/GDD30) and their effect on fruit size. Moreover, a predictive model to estimate the number of days between the full bloom and harvest date based on GDH30 (Mimoun and DeJong 1999; Lopez and DeJong 2007) and GDD30 (Kenealy et al. 2015; Reighard and Rauh, 2015) was developed for peach growers. However, the relationship between GDD/GDH accumulation from full bloom to ripening time and FDP, as well as the stability of these phenological traits within breeding germplasm, have not been thoroughly investigated. Therefore, we calculated GDD, GDH and FDP for peach material from the Clemson University breeding program and assessed their variability across six growing seasons. In addition, we identified phenologically stable accessions in one or more of the investigated traits, as potential resources for enhancing climate resilience in breeding germplasm.

Materials and Methods

A total of 97 advanced breeding lines (accessions) from the Clemson University peach breeding (CUPB) program were included in the study. Material was grown at the Clemson University Musser Fruit Research Center (lat. 34.639038, long. -82.935244) under warm, humid, temperate climate and standard commercial practices for irrigation, fertilization and pest and disease control. The trees were at least five years old, grafted on Guardian® rootstock, grown in duplicate, with 4 × 6 m spacing and trained as ‘open center’. Material was selected based on the availability and completeness of weather and phenological (bloom and ripening date) data. Phenological trait data, bloom (BD) and ripening date (RD)

were collected, and fruit development period (FDP) was calculated as number of days between the BD and RD over six consecutive growing seasons (2018 – 2023). Full bloom was considered when 90% or more flowers were fully open. The time of fruit harvest was determined based on fruit size, color change and loss of firmness by visual observation. BD and RD were converted to day-of-year (DOY) number and used in downstream statistical analyses. Inter-annual variation in BD, RD, and FDP was investigated and the standard deviation (Std Dev) and range (maximum – minimum) of BD, RD, and FDP across years were calculated to assess phenological stability of each trait per accession. The percentile-based thresholds (25th and 75th percentiles of Std Dev) were computed per trait to identify stable, moderately variable, or unstable accessions. The following stable and unstable thresholds per trait were determined in this dataset: BD: ≤ 7.61 and ≥ 8.94 ; RD: ≤ 5.34 and ≥ 7.39 ; FDP: ≤ 5.35 and ≥ 8.04 , respectively. All plots were generated using Python libraries including *pandas* (McKinney 2010), *matplotlib* (Hunter 2007), and *seaborn* (Waskom 2021). Kernel density estimation (KDE) overlaid in histograms was applied using default settings based on Rosenblatt (1956) and Parzen (1962).

The hourly temperature data was obtained from the Davis Vantage Pro2 (Davis Instruments, Hayward, CA USA) weather station at Musser Fruit Research Center, Seneca, SC. In two seasons, 2018 and 2019, only daily average, min and max temperature data were available, so these two seasons were excluded from the GDH calculation. GDDs were calculated for all six seasons (2018-2023) 30 days after full bloom (GDD30) and from the full bloom to the ripening time (GDD) using the Baskerville-Emin (1969) method with a base temperature of 7 °C as utilized in Kenealy et. al (2015). GDHs were calculated 30 days after full bloom (GDH30) and from the full bloom to the ripening time (GDH), for 4

seasons (2020-2023), using Anderson et al. (1986) method with a base temperature of 7 °C. Variability and correlation between the GDD / GDH and FDP were analyzed and graphically presented using JMP Pro (ver. 17, SAS Institute Inc., Cary, NC).

Results and Discussion

Phenological data (BD, RD and FDP) observed in peach germplasm evaluated in this study were highly variable and influenced by the season (Figure 1; Tables S1, S2). Overall, out of 97 accessions included in the study, the earliest BD and RD were recorded in 2023, in 95 and 92 accessions, respectively. Similarly, the latest BD (70%) and RD (77%) were observed in the 2022 season. Most accessions (90%) had both the earliest BD and RD in the same season, 2023. Median BD spanned from February 25 to March 20, with lowest variability (16 days) observed in two accessions SC10-23-0155 and SC10-38-162 and largest, over a month difference (32 days) between the earliest and latest recorded BD, observed in SC08-16-122. The shortest BD range was recorded in 2023 and the longest in 2018 and 2019. Longer BD range is more desirable in breeding programs as it allows for more cross combinations to be achieved.

The timing and sequence of bloom are genetically regulated by chilling requirement,

as well as by the duration and timing of cold and warm temperature exposure experienced by the buds (Campoy et al. 2011; Fadon et al. 2020; Okie and Blackburn 2011). However, the progression of flower opening in peach can vary dramatically from taking days to just hours, influenced by both the quality of chill and total chilling accumulation during endodormancy and the heat accumulation during ecodormancy (Cifuentes-Carvajal et al. 2023; Okie and Blackburn 2011). Median RD ranged from May 24 to August 10, with one week (6 days) to over a month (34 days) difference between the extremes. The RD range was similar between the seasons reflecting underlying genetic differences between the accessions. Variation in BD and RD was also evident in the FDP, whose median values ranged from 72-152 days from full bloom to harvest. Similar to RD, the FDP range across six seasons spanned from 7-32 days, with highest and lowest variation observed during the June 15-30 ripening period (Table S1).

Phenological stability of each trait per accession, calculated using standard deviation (Std Dev) and range (maximum – minimum) of BD, RD, and FDP across years, and their distribution provided a quantitative measure of year-to-year phenological variability (Figure 2; Table S2). Traits with lower Std Dev and

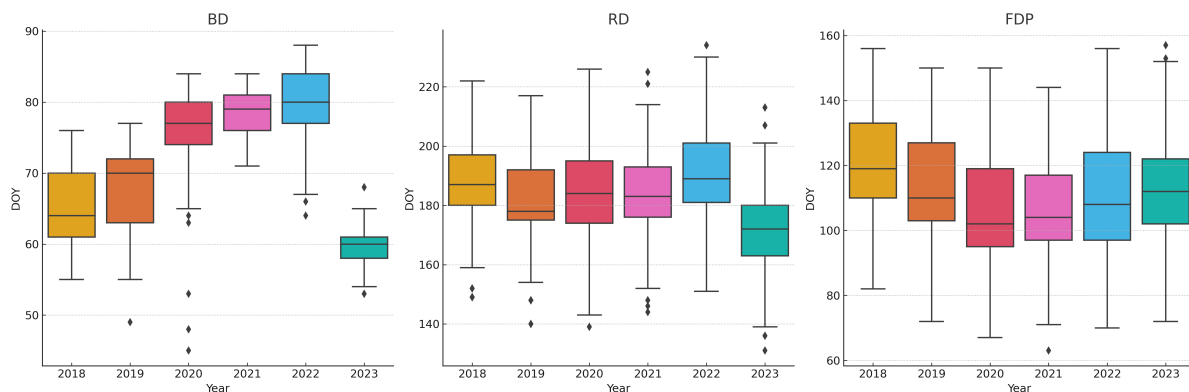


Figure 1. Phenological observations, bloom date (BD), ripening date (RD) and number of days between the BD and RD, fruit development period (FDP), in 97 peach accessions from Clemson University peach breeding program observed in Seneca, SC from 2018 - 2023. Each box represents the interquartile range, with the horizontal line denoting the median day of year (DOY). Whiskers indicate variability outside the upper and lower quartiles.

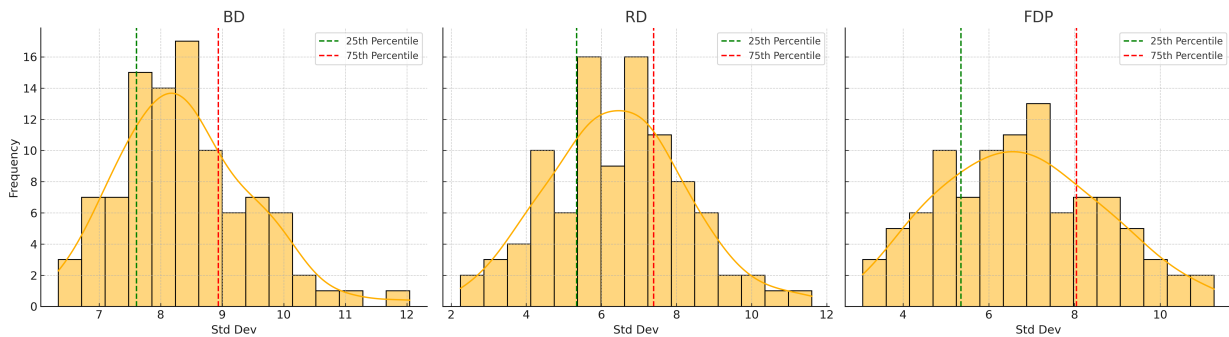


Figure 2. Distribution of standard deviation (Std Dev) in bloom date (BD), ripening date (RD), and number of days between the BD and RD, fruit development period (FDP) across six years (2018–2023) for 97 individual accessions in Clemson University peach breeding program. Green and red dashed lines indicate the 25th and 75th percentiles, respectively.

accessions in the 25th percentile are considered more phenologically stable across years. Of the 97 accessions included in the study, only three accessions – SC10-23-155, SC08-29-009 and SC09-01-024 – exhibited stable phenotypes in all three traits across all seasons. Individual BD, RD and FDP stability was observed in 21, 26 and 22 accessions, respectively. This information will support the CUPB program in developing climate-resilient peach germplasm with targeted stability across all traits or specific trait combinations. Additional seasons and a larger number of accessions and cultivars are needed to validate these findings. Seasonal variability in BD and RD in South Carolina was reported earlier (Atagul et al. 2022) with RD often being affected by human subjectivity in assessing the time of harvest. Therefore, variability observed in FDP and GDD/GDH data between the growing seasons may be attributed to a human error in determining when to harvest. The most common indicators of fruit maturity used to determine when to harvest are fruit size and color, which are inherently subjective. Fruit firmness or index of fruit maturity (Spadoni et al. 2016) data would provide definitive evidence if the harvest times recorded in the six seasons used in this study were influenced by human error.

Heat accumulation was variable in the experimental years regardless of the heat unit, GDD30, GDH30, GDD or GDH (Table S3). Median heat accumulation expressed in GDD30 ranged from 376 – 463 and GDH30 from 6,763 – 8,156 with difference in minimum to maximum heat accumulation 30 days after the full bloom (HAD30) ranging from 159 – 320 GDD and 1,053 – 3,300 GDH (Table S3). Median range of heat accumulation between BD and RD was 1,279 – 3,918 GDD and 19,476 – 56,222 GDH. Interestingly, the extreme values of heat accumulation range, expressed as GDD, aligned with the extremes in RD: the lowest accumulation was observed in the earliest-ripening accession (SC08-13-001), while the highest was recorded in the latest-ripening accession (SC25P). The application of heat accumulation metrics, such as GDD and GDH, has been shown to be effective for optimizing thinning timing in peach cultivation (Lopez and DeJong 2007; Kenealy et al. 2015). Fruit development has been found to be strongly influenced by heat accumulation during the first 30 days after bloom (GDH30), with higher values leading to earlier ripening and, in some cases, smaller fruit size due to reduced duration for growth (Lopez and DeJong 2007). Thinning

conducted early in relation to heat accumulation has consistently been associated with improved fruit size, quality, and marketable yield, as more efficient resource allocation among developing fruits is facilitated when thinning is aligned with GDH thresholds (Grossman and DeJong 1995; Kenealy et al. 2015; Ray et al. 2022). The threshold of 6,000 GDH30 is well-established in peach production as a critical point for initiating early thinning (Lopez and DeJong 2007; Lopez et al. 2010; Kenealy et al. 2015). There is currently no formally recognized equivalent threshold in GDD30 used for orchard management decisions. Using our multiyear dataset, which includes both GDH30

and GDD30 values across several seasons, we identified that 6,000 GDH30 corresponds approximately to 365 – 400 GDD30 during the first 30 days after bloom. Analysis of our dataset indicates that heat accumulation during the first 30 days after full bloom, when GDH30 exceeds 6,000 and GDD30 surpasses 365, is consistently associated with the need for early thinning in most seasons.

To assess the consistency of heat accumulation and fruit development across years, we evaluated interannual variability using the coefficient of variation (CV). The CV, which estimates the relative dispersion of values around the mean, was less than 11.3% for FDP, 16.7% for GDD, and 17.8% for GDH

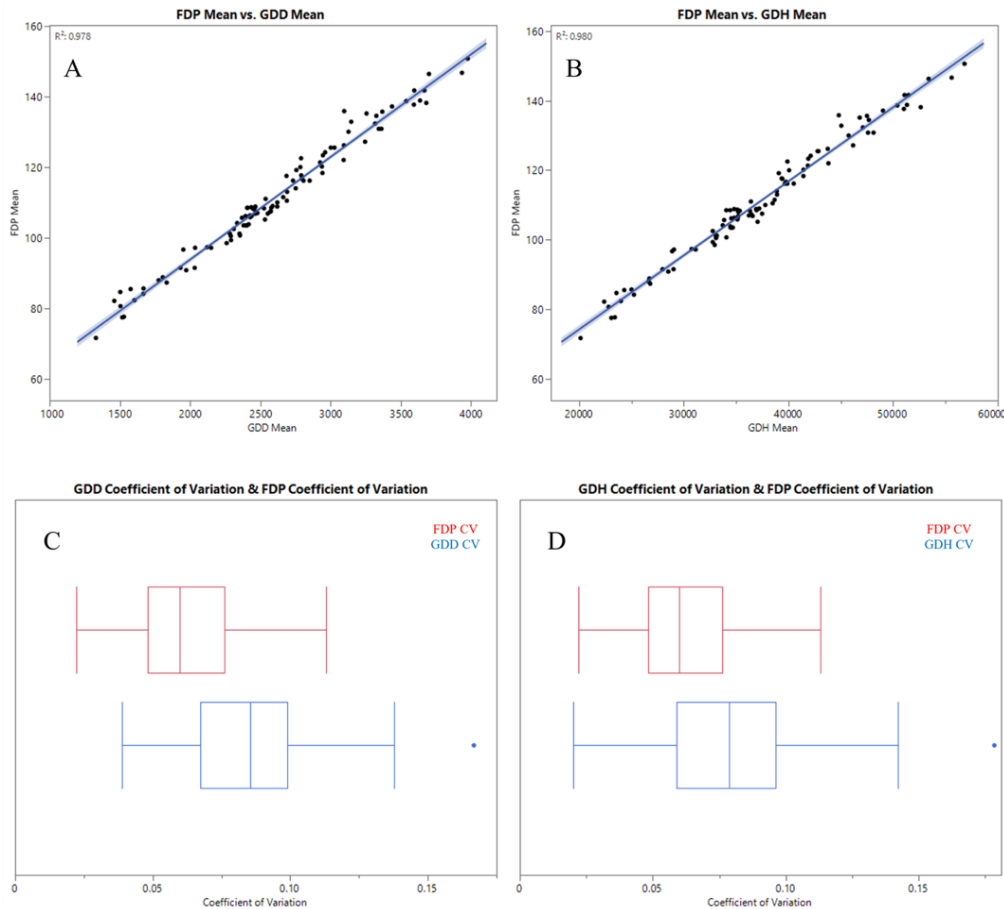


Figure 3. Correlation (A & B) and coefficient of variation (CV) (C & D) between growing degree days (GDD) or growing degree hours (GDH) and fruit development period (FDP) in 97 peach and nectarine accessions from the Clemson University peach breeding program, evaluated over six (GDD) and four (GDH) growing seasons (2018-2023 and 2020-2023, respectively). Data is presented as six- and four-year averages.

across all accessions, indicating relatively low deviation over the six experimental years (Figure 3). Most accessions (78% and 69%) exhibited lower CV values for FDP than for GDD and GDH, respectively. Moreover, boxplot analyses demonstrated that both GDD and GDH were more variable relative to the mean compared to FDP over six years (Figures 3C; 3D). Differences in variability between the FDP and the heat accumulation metrics were statistically significant, with p-values of 8.79×10^{-11} (FDP vs. GDD) and 4.31×10^{-6} (FDP vs. GDH), which was supported by the observed average CV values, 6.2% for FDP, 8.4% for GDD, and 7.9% for GDH. In addition, we observed a strong positive linear correlation between FDP and both heat accumulation metrics, with the coefficient of determination (R^2) 0.978 for FDP vs. GDD (Figure 3A) and 0.980 for FDP vs. GDH (Figure 3B). Differences in variability between GDD and GDH CV values were not statistically significant ($p = 0.195$).

Marra et al. (2002) observed lower CV and higher predictive ability, in terms of days, of GDH than both GDD and FDP in three peach and two nectarine cultivars across 3-9 experimental seasons. The early forecasting of harvest time (RD) showed better accuracy than the one calculated from climatic data during the whole FDP. In addition, GDD observed during full FDP in their study was half of that observed in ours, 639-1,977 vs. 1,279-3,918 while GDH was comparable, 22,779-56,893 vs. 19,476-56,222. The observed differences could be due to the different approach in calculating heat accumulation (different base temperatures and methods, they used Linvill, 1990), obtaining phenological data (e.g. full bloom considered at 50-70% flowers open), climate in California vs South Carolina, and the broader FDP range in material analyzed, 50-170 vs. 72-152 in our study.

Overall, our findings indicate that both GDD and GDH exhibit greater variability around the mean compared to FDP, despite

their adaptability to climate fluctuations and independence from calendar-based timing. As expected, the variation in heat accumulation did not significantly differ between the two estimation methods, suggesting that both metrics are comparably effective for modeling seasonal thermal dynamics. The average CV across all methods was below 10%, with no method exceeding 20%, even in the most variable accessions. From a commercial production standpoint, the difference in variability between GDD, GDH and FDP may be practically insignificant, suggesting that growers can confidently use any of these models to guide orchard management decisions. However, because FDP requires only bloom and harvest dates, it presents a valuable alternative for producers who may lack access to detailed weather data needed for calculating heat accumulation. Therefore, we recommend that breeding programs and extension services include FDP information in peach cultivar descriptions, providing growers with a practical and reliable option for estimating ripening time.

Moreover, because GDD and GDH are sensitive to interannual temperature fluctuations, they hold promise for use in forecast-based orchard management tools, particularly when integrated with long-range weather predictions. Further research evaluating GDD, GDH, and FDP stability across multiple locations and over a longer temporal scale, ideally using well-characterized reference cultivars, should validate the robustness of these metrics and confirm the correlations observed in this study.

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