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Rest Completion Prediction Model for 'Starkrimson Delicious' Apples

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Abstract. **A chill unit model was developed for 'Starkrimson Delicious' (*Malus domestica* Borkh.) apples grown under the wide range of temperature and elevations in North Carolina. The model relates air temperature to effective chill units and predicts rest completion for North Carolina-grown apples more accurately than previously reported models. The model proposes a broader range of effective temperatures and incorporates a greater negative effect when temperatures exceed 21°C for rest. According to the model, 1200 chill units are required to break rest of apple buds. Growing degree hours correlated with each apple bud developmental stage, as well as from projected date of rest completion to full bloom, were determined using various base temperatures.**

Quantitative measurements of chilling requirement of tree fruit buds to terminate rest have been reported for many species and cultivars. This requirement generally is expressed either as the number of hours below a certain temperature, usually 7.2°C (7, 8, 9, 23, 24), or as a weighted chill unit (CU) corresponding to different temperatures during winters (10, 11, 18, 19). Total hours below 7.2° required for rest termination shows considerable variation (16, 19) and does not account for any chilling above 7.2° (2, 3, 12, 17, 22, 24).

Erez and co-workers (10, 11), working with peach under controlled conditions, developed a weighted chilling hour model wherein 3° and 8°C were 90% as effective 6°, while 10° was only 50% as effective. Temperatures of 18° or lower did not negate chilling while temperatures of 21° to 24° resulted in full reversion of chilling effect.

Richardson et al. (18, 19) proposed a weighted CU model in Utah where one CU equals 1 hr of exposure at 6.1°C. CU accumulation becomes less than one as temperature deviates from that optimum. A negative contribution occurs above 15° and zero units are accumulated below 1.4°. The "Utah model" did not predict the end of rest when tested under mild conditions (4, 13, 14, 25).

Freeman and Martin (12) reported that 10°C was half as effective as 6° in chilling peach flower buds. Researchers (2, 17) found that 21° alternated with 4° in daily cycles slowed vegetative budbreak of peaches and pears.

The objectives of this study were to: 1) examine the reliability of the Utah model, the total hours below 7.2°C and the number of hours between 0.0° and 7.2° for predicting rest completion in 'Delicious' apple; 2) develop an accurate model for predicting rest completion under North Carolina conditions; and 3) predict the energy requirement associated with each apple bud developmental stage.

Materials and Methods

Fifty twigs, 40- to 50-cm-long, were collected periodically from bearing 'Starkrimson Delicious' apple trees on seedling rootstocks at 5 locations in North Carolina. These were Wake County (128-m elevation), Cleveland County (335-m elevation), Wilkes County (677-m elevation), Henderson County (683-m elevation), and Mitchell County (792-m elevation). Twigs were taken into the greenhouse at 18° to 21°C and placed in containers containing a solution consisting of 3.8% (w/v) 8-hydroxyquine-line citrate and 0.033% (w/v) aluminum sulfate. Data on bud

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development was obtained every other day and percentage of budbreak calculated after 21 days of forcing.

Orchard temperatures were recorded by a thermograph placed in protected weather shelters about 1.5 m above ground level in each orchard. Temperatures were determined to ± 0.6°C. To compute fulfillment of chilling requirements, 2 techniques were used and compared to the experimental model developed in this study: 1) accumulation of 1234 CU units according to the Utah model (18); and 2) accumulation of 1440 hr below 7.2°C (6). To determine the CU accumulation for a 24-hr period, a computer was programmed to convert each hourly temperature to the equivalent values of chilling. These values then were added for the entire 24-hr period. The best CU model which explained the variation in rest fulfillment at the various locations was then derived from the computer comparisons as well as from floral budbreak data and dates of full bloom vs. orchard temperature data. Calculation of effective chilling hours was initiated the following day after attainment of largest negative accumulation as described by the Utah group (19). This model correlates temperatures with hourly CU values.

Growing degree hours (GDH) required to reach different bud developmental stages were calculated using the Utah model (18), a base temperature of 4.4°C (21), and a base temperature of 6.1° (5, 20).

Results and Discussion

Rest period was considered to be broken when budbreak plateaued with no further significant increase in the percentage of budbreak from one sample date to the next. Higher elevations (Henderson, Mitchell, and Wilkes counties) completed their chilling requirements earlier than lower elevations (Wake and Cleveland counties). As the chilling hours increased, the percentage of budbreak also increased (Tables 1, 2, 3).

The Utah model represents effective bud temperature based on air temperature measured in an instrument shelter (16), Fig. 1. The actual temperature and corresponding CU values for the curve of the North Carolina model are presented in Table 4. The North Carolina model (Fig. 1) is broader and shows a higher optimum chilling peak at 7.2°C (6.1° for Utah model) as well as a greater negative effect with temperatures above 21° reaching maximum chilling negation (−2.0 CU) at 23.3°. The greatest difference between the Utah model and North Carolina model is the contribution of the curve between 7.2° and 19.5°. This segment is very important in warmer climates, since temperatures during winter often fall within this range. Assigning CU between 7.2° and 19.5° may be the reason for the failure of the Utah model to predict rest termination accurately under mild conditions (Tables 5 and 6). At temperatures above 18° there was an increase in chilling negation as compared to Utah model. This negative effect increased steeply and reached its maximum (−2.0 CU) at 23.3°. At the lower temperature cut-off for CU accumulation, there were some differences between the Utah model (cut-off at +1.4°) and the North Carolina model (cut-off −1.1°). (Fig. 1).

The North Carolina model differs in 3 ways from the Utah model: 1) it assigns greater chilling contribution to the lower temperatures down to the cut-off of −1.1°C. This agrees with models reported on other crops (1, 3, 7, 15); 2) it assigns more negative effect to temperatures above 21° reaching −2.0 CU at temperatures of 23.3° and higher. These results agree with those found by Erez et al. (10, 11) on peaches; and 3) the North Carolina model assigns chilling contribution near zero for temperatures between 16° and 18°. This model was more accurate than other models for predicting rest completion under North Carolina conditions (Table 5).

Table 1. Percentage of flower budbreak of excised 'Starkrimson Delicious' shoots in 1978 after 21-day forcing period at 18° to 21°C.

	Budbreak (%)				
	Locations (N.C. counties)				
Date Sampled	Wake	Cleveland	Wilkes	Mitchell	Henderson
Jan 16, 1978	0.0 e[z]	0.0 d	29.8 c	30.2 c	25.4 c
Jan 30, 1978	18.2 d	20.0 c	84.4 b	80.8 b	82.0 b
Feb 5, 1978	72.4 c	75.0 b	100.0 a[y]	99.8 a[y]	99.8 a[y]
Feb 17, 1978	87.8 b	97.6 a[y]	100.0 a	100.0 a	100.0 a
Feb 27, 1978	98.8 a[y]	100.0 a	100.0 a	100.0 a	100.0 a
Mar 5, 1978	100.0 a	100.0 a	100.0 a	100.0 a	100.0 a
Mar 16, 1978	100.0 a	100.0 a	100.0 a	100.0 a	100.0 a
LSD 5%	2.58	2.51	2.26	2.92	1.79

[z]Mean separation within column by Fisher's LSD, 5% level.
[y]Date considered as the date of rest completion.

Table 2. Percentage of flower budbreak of excised 'Starkrimson Delicious' shoots in 1979 after 21-day forcing period at 18° to 21°C.

	Budbreak (%)				
	Locations (N.C. counties)				
Date Sampled	Wake	Cleveland	Wilkes	Mitchell	Henderson
Dec 13, 1978	0.0 c[z]	0.0 f	0.0 d	0.0 d	0.0 d
Jan 13, 1979	0.0 c	6.2 e	19.0 c	20.0 c	15.0 c
Jan 30, 1979	20.0 d	25.2 d	90.0 b	80.0 b	84.0 b
Feb 2, 1979	70.2 c	75.8 c	97.8 a[y]	96.0 a[y]	97.7 a[y]
Feb 15, 1979	90.0 b	90.0 b	98.0 a	98.0 a	98.0 a
Feb 23, 1979	98.4 a[y]	98.0 a[y]	98.0 a	98.0 a	98.0 a
Mar 7, 1979	98.4 a	98.4 a	99.0 a	98.0 a	98.0 a
Mar 15, 1979	100.0 a	100.0 a	100.0 a	100.0 a	100.0 a
LSD 5%	2.77	2.76	2.27	4.48	2.32

[z]Mean separation within columns by Fisher's LSD, 5% level.
[y]Date considered as the date of rest completion.

Table 3. Percentage of flower budbreak of excised 'Starkrimson Delicious' shoots in 1980 after 21-day forcing period at 18° to 21°C.

	Budbreak (%)				
	Locations (N.C. counties)				
Date Sampled	Wake	Cleveland	Wilkes	Mitchell	Henderson
Jan 1, 1980	0.0 e[z]	0.0 d	12.0 c	15.2 c	10.2 c
Jan 25, 1980	25.0 d	30.0 c	90.0 b	90.0 b	87.6 d
Feb 1, 1980	70.0 c	78.0 b	98.2 a[y]	97.8 a[y]	98.7 a[y]
Feb 11, 1980	89.0 b	98.2 a[y]	100.0 a	100.0 a	100.0 a
Feb 18, 1980	98.0 a[y]	100.0 a	100.0 a	100.0 a	100.0 a
Mar 6, 1980	100.0 a	100.0 a	100.0 a	100.0 a	100.0 a
Mar 14, 1980	100.0 a	100.0 a	100.0 a	100.0 a	100.0 a
LSD 5%	3.46	1.96	2.17	2.53	1.33

[z]Mean separation within column by Fisher's LSD, 5% level.
[y]Date considered as the date of rest completion.

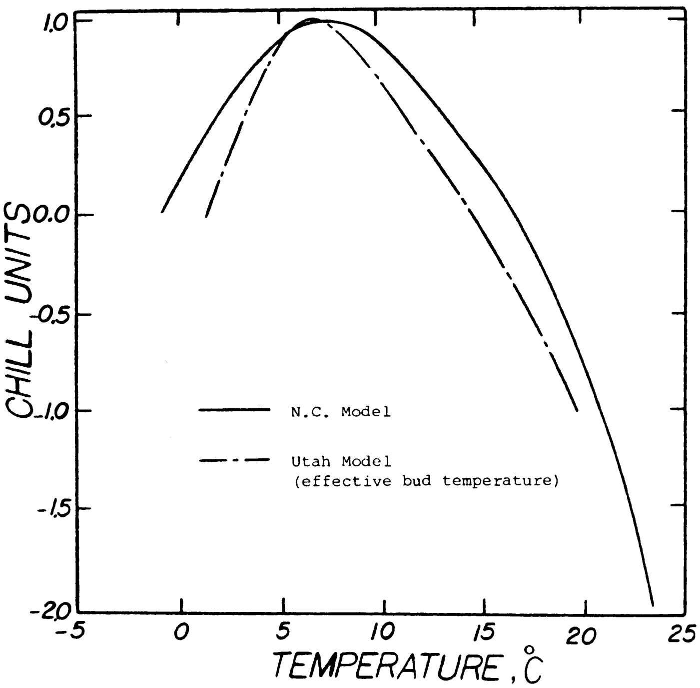

Fig 1. Comparison of chill units to temperature for 'Starkrimson Delicious' apple under North Carolina conditions with Utah model vs. North Carolina model.

With the total hours below 7.2°C model, the trees accumulated 1842 CU in the average of years and locations. Total hours below 7.2° was consistent from year to year within and between the higher elevations with a maximum difference of 198 CU, whereas large differences appeared within the lower elevations from year to year (averaging 350 CU). There was a substantial difference between the lower and higher elevations in the total hours required to break rest, except for 1978–1979 (the coldest year) where the difference between the lower and higher elevations was negligible. In New York, Eggert (9) found that 'Delicious' apples require 3542 CU below 7.2°, and 1303 between 0.0° and 7.2°, while Chandler (6) found that under California conditions, 1440 CU were sufficient for breaking rest of 'Delicious' apples. In 1980, under North Carolina conditions, 3542 chilling hours below 7.2° were not accumulated by the time of visible growth of apple trees, especially at the lower elevations. At the same time, it seems that 1440 chill hours below 7.2° are not enough for breaking rest of apples under North Carolina conditions. The actual accumulation between years and locations ranged from 1550 to 1982 chilling hours.

Table 4. Corresponding temperature and chill unit value of North Carolina model.

Temp (°C)	Chill Unit contribution
−1.1	0.0
1.6	0.5
7.2	1.0
13.0	0.5
16.5	0.0
19.0	−0.5
20.7	−1.0
22.1	−1.5
23.3	−2.0

Table 5. Accumulated chill units at optimum flower budbreak of 'Starkrimson Delicious' apple using various models.

		Accumulated chill units			
Location (N.C. counties)	Year	Hours below 7.2°C	Utah model	Hours between 0° to 7.2°C	N.C. model
Wake	1977–1978	1950	958	1106	1196
	1978–1979	1650	958	978	1200
	1979–1980	1550	926	1004	1202
Cleveland	1977–1978	1980	913	960	1205
	1978–1979	1803	920	1004	1200
	1979–1980	1680	963	970	1214
Wilkes	1977–1978	1910	880	760	1200
	1978–1979	1784	880	862	1210
	1979–1980	1800	890	870	1205
Mitchell	1977–1978	1982	982	778	1207
	1978–1979	1934	1034	1006	1216
	1979–1980	1818	1203	1064	1200
Henderson	1977–1978	1964	890	858	1200
	1978–1979	1936	941	970	1195
	1979–1980	1900	961	922	1205
Avg		1842	956	940	1203
Suggested rest completion value		1440	1234	1300	1200

As has been suggested (16, 19), the total hours below 7.2° is not accurate since it differs by years and location.

When comparing the Utah model (1234 CU) with the actual budbreak data in North Carolina (Table 5), the average between years and locations was only 956 CU, suggesting that the trees never received sufficient chilling. However, since apple trees at all locations broke normally and did not show any sign of lacking chilling, it has to be assumed that the Utah model is not suitable for calculating chilling in mild or highly variable climates. With the hours between 0.0° and 7.2°, the average CU accumulation was 940. This was consistent from year to year within a specific location but was not consistent between locations for a given

Table 6. Growing degree hours (GDH) required for 'Starkrimson Delicious' apple bud development from time of calculated rest completion to full bloom using different models.

	North Carolina environment			Utah environment
Stage of fruit bud development	GDH[z] 4.4	25[y] GDH 4.4	GDH[x] 6.1	25 GDH (Utah)[y] 4.4
Silver tip	2096	2078	1846	2061
Green tip	2606	2586	2296	2544
1.3 cm green	3266	3239	2877	3100
Tight cluster	4100	4066	3610	3939
First pink	5007	4966	4412	4856
Full pink	5540	5495	4882	5394
First bloom	6325	6274	5575	6172
Full bloom	7082	7024	6242	6933

[z] $GDH = \sum_{n=1}^{12} (Tm - 4.4)\ 2$, where Tm = temperature at a given hour in the day; 4.4°C = base temperature.

[x] $GDH = \sum_{n=1} (Tm - 6.1)\ 2$, where Tm = temperature; 6.1°C = base temperature.

[y] $GDH = \sum_{4.4}^{25} \sum_{n=1}^{12} (Tm - 4.4)\ 2$, where Tm = 4.4°C if temperature <4.4°C; Tm = 6.1°C if temperature is >25°C.

Table 7. Actual and calculated bloom dates of 'Starkrimson Delicious' apple using different models.

Location (N.C. counties)	Year	Actual bloom date	N.C. model: Calculated date	N.C. model: Difference in days[z]	Hr <7.2°C: Calculated date	Hr <7.2°C: Difference in days[z]	Utah model: Calculated date	Utah model: Difference in days[z]
Wake	1978	Apr 10	Apr 10	0	Apr 9	1	y	y
	1979	Apr 13	Apr 8	5	Apr 3	10	y	y
	1980	Apr 11	Apr 11	0	Apr 8	3	May 2	21
Cleveland	1978	Apr 10	Apr 10	0	Apr 10	0	y	y
	1979	Apr 16	Apr 12	4	Apr 8	8	y	y
	1980	Apr 15	Apr 15	0	Apr 13	2	May 1	16
Wilkes	1978	Apr 11	Apr 13	2	Apr 13	2	May 11	30
	1979	Apr 18	Apr 18	0	Apr 18	0	Apr 27	9
	1980	Apr 19	Apr 18	1	Apr 18	1	Apr 26	7
Mitchell	1978	Apr 18	Apr 22	4	Apr 22	4	May 9	21
	1979	Apr 26	Apr 24	2	Apr 18	8	May 4	8
	1980	Apr 28	Apr 28	0	Apr 20	8	May 4	6
Henderson	1978	Apr 15	Apr 17	2	Apr 17	2	May 8	23
	1979	Apr 21	Apr 16	5	Apr 10	11	May 1	10
	1980	Apr 25	Apr 25	0	Apr 15	10	May 3	8

[z]Difference between actual bloom data and model calculated bloom date.
[y]Trees reached bloom date before enough calculated accumulation of chilling.

year. Thus, neither the Utah model, the total hours below 7.2°, nor the hours between 0.0° and 7.2° model was very accurate under North Carolina conditions. With the North Carolina model, about 1200 CU were accumulated (Table 5) at time of rest completion, with only 10 CU difference between locations and year. This was within 2 days of the actual forcing data. The time of rest completion was estimated to be about the first week of February in the higher elevation and about the 3rd week of February in the lower elevations.

The GDH required to reach various bud developmental stages from time of rest completion through full bloom using different base temperatures (4.4° and 6.1°) and the "Utah" model is presented in Table 6. When total GDH accumulations were considered from dormant bud to full bloom, all North Carolina orchards were close to 7042 using the Utah model, whereas under Utah conditions 6933 GDH was required. A total of 7082 GDH was calculated using 4.4° as the base temperature and 6242 using 6.1° as the base temperature. Using a chill requirement of 1200 CU for 'Starkrimson Delicious' apple and 7082 GDH, dates of full bloom were calculated for each year at the 5 locations. The differences between calculated and observed date of full bloom was determined for each year at all locations (Table 7). The differences between observed and calculated bloom with the North Carolina model ranged from 0 to 5 days with an average of 2 days between years and locations. Calculated and observed dates from projected rest completion to full bloom using the other models is presented in Table 7. Since the North Carolina model has lower differences between calculated and observed bloom dates than other models over the 3 years and 5 locations sampled, it is considered more accurate.

Table 8. Initiation dates of chilling of 'Starkrimson Delicious' apple in different locations in North Carolina[z].

Year	Wake	Cleveland	Wilkes	Mitchell	Henderson
	Initiation dates of chilling — Locations (N.C. counties)				
1977–1978	Oct 9	Oct 9	Oct 3	Oct 2	Sept 27
1978–1979	Oct 14	Oct 6	Oct 5	Sept 28	Sept 26
1979–1980	Oct 23	Oct 23	Oct 5	Oct 3	Sept 30

[z]Based on accumulation starting the following day after maximum negative occurs.

The initiation of CU accumulation on the day following the day of largest negative accumulation as reported by Richardson et al. (19) is considered accurate. The day of largest negative CU accumulation was about the same in the higher elevation over years but varied in lower elevations (Table 8). The maximum difference in day of chilling onset within specific locations, from year to year, was 4 days in higher elevations and 17 days in lower elevations. These large differences stress the need for more work to determine the time to begin calculating effective chilling in the fall.

Using the Utah model to compare bloom development stages under North Carolina conditions indicates that the GDH model operates similarly in both Utah and North Carolina. The maximum difference was 127 GDH on tight cluster with a difference of only 91 units at full bloom. Thus, the GDH needed to reach several stages of apple bud development did agree to a great extent with those obtained by Richardson et al. (18).

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