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Adjusting Growth Stage Values to Develop a Linear Scale for Apricot Flower Bud Phenology

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Abstract. **Integer values used to represent apricot (*Prunus armeniaca* L.) flower bud growth stages in a phenological scale were adjusted by a simple technique based on cumulative counts of bud observations. Adjusted stage values on a new continuous scale were calculated so that differences between consecutive values were proportional to the frequency with which buds were observed in each growth stage class during the entire assessment period. This meant that adjusted scale values were linearly related to bud development rate at 20 °C. The method was applied to a scale describing flower development from budbreak to petal fall for three cultivars of apricot growing under orchard conditions.**

Phenological scales commonly rank developing organs and plants by means of readily distinguishable growth stages, each given a name and a letter or number (Fleckinger, 1955; Gepts, 1987; Zadoks et al., 1974). Scales of this type are useful, as they describe the stage of development more precisely than calendar dates and permit standardized description across different cultivars. Moreover, they can be related to developmental characteristics, such as critical temperatures for freeze injury, which may be predicted using chill unit, and growing degree hour (GDH) summation (Lombard and Richardson, 1979).

A crucial feature of phenological scales is the reliable recognition of growth stages under field conditions, without specialized equipment. The time interval between stages may therefore vary greatly in order that each stage is readily distinguished. However, adjustment of stage values to create a linear relationship between the scale and developmental time appears not to have been attempted. Hence, existing scales typically use letters or evenly-spaced number rankings for growth stages, so that the chronological rate of progress through them is nonlinear (Brown and Abi-Fadel, 1953; Fleckinger, 1955; Gepts, 1987; Guerriero et al., 1986; Tabuenca, 1968). Differences in flower bud appearance in apricot are less distinct soon after budbreak than near bloom. Consequently, early stages in scales used to describe bud development appear prolonged relative to later stages (Tabuenca, 1968).

This situation means that apparent developmental rates (expressed in scale units) vary artificially throughout the scale, even under constant growing conditions. This restricts scale use because rates measured at different points in the scale cannot be compared with one another. Describing the relationship of development to environment is also more complex, and simple linear functions cannot be used to summarize development. This paper, therefore, outlines a technique to adjust integer stage values of phenological scales to create a linear relationship with development. The technique is applied to a phenological scale for apricot flower bud development using data collected under constant temperature conditions. This adjusted scale is then used to describe the progression of bud population phenophases under field conditions.

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Materials and Methods

Cuttings of 'Royal Rosa', 'Sundrop', and 'Trevatt' apricot cultivars, 15–20 cm long and bearing at least four flower buds, were prepared from branches collected from mature trees in three commercial orchards in Hawkes Bay, New Zealand, on 30 June, 17 July, and 31 July 1992 (i.e., midwinter). Chilling accumulation in the orchard reached ≈1000 chill hours (h < 7 °C) by the end of July, the time of natural budbreak. Multiple cuttings were taken from each branch while it was submerged under water. All flowers were carried on 1-year-old shoots (nonextension wood) and all cuttings were terminated by vegetative buds. Cuttings were disinfested for 1 h in 8-hydroxyquinoline sulphate at 33 $g{\cdot}L^{-1}$ and placed individually in 30-mL vials of tap water (replaced twice weekly). Trays of 60 vials were placed in clear polyethylene bags to minimize evaporative stress. All cuttings were forced at 20 ± 1 °C under fluorescent light (60–80 $\mu mol{\cdot}m^{-2}{\cdot}s^{-1}$) and a 12-h photoperiod.

Bud development was assessed twice weekly for up to 4 weeks. A few cuttings were observed for up to 6 weeks where buds showed signs of growth. 'Sundrop' flower buds are borne singly and in pairs on 5- to 15-cm spurs growing at intervals along older branches, 1–2 cm in diameter, but on 'Royal Rosa' and 'Trevatt' they are clustered at branch ends on the youngest twigs. 'Sundrop' cuttings therefore consisted of single spurs bearing 3 to 10 buds and a section of supporting branch. Those of 'Royal Rosa' and 'Trevatt' consisted of twigs alone. The development of all buds was recorded but only data for the first-moving buds on each cutting was used for this analysis, as later-moving buds often aborted, possibly due to competition for resources within the small shoots. This was true especially for 'Trevatt'.

Assessments were made using a ten-stage scale (Fig. 1). This scale was based on an earlier scale (Fleckinger, 1955), modified by dividing the original first stage into three new stages to shorten the time between stages. The original alphabetic scale was also replaced by a numeric scale to permit expression of fractional stage values and to simplify data manipulation. Each stage value was then adjusted using count data summarizing the entire assessment period. The adjustment was based on the cumulative proportion of all observations of buds at preceding stages to the one adjusted. This procedure follows from the expectation that equal numbers of buds at each developmental stage should be counted over the assessment period if a) bud development progresses at a constant rate (i.e., each scale stage has an equal transit time) and b) observations are made at regular intervals that are less than the expected average stage transit time. If equal numbers are not counted, then a plot of the cumulative proportion of all bud stage observations will be nonlinear. This information can then be used to adjust the scale values for recognized stages (e.g., "anthesis" or "petal fall") so that intervals match the actual duration of time between the stages.

Hence, adjusted scale values (s') were obtained by using the following formula:

$$s_i' = s_0' + (s_u - s_0)\sum_{s_0}^{s_{i-1}} p_i \quad ; \quad 1 \le i \le n_s - 1$$

where i is the scale index position for a recognized stage, s_0 and s'_0 are values for the lower boundary stage (here $s_0 = 0$ and $s'_0 = 0$ for "dormant" buds), s_u is the value for upper boundary stage (here $s_u = 9$), p_i is the proportion of all bud observations at stage s_i, and n_s is the number of scale intervals between s_0 and s_u. This method can be applied to any numeric scale. The integer range 0–9 used in this instance was chosen for convenience and is otherwise quite arbitrary. Only scale values $i = 1$ through to $i = n_s - 1$ were adjusted, since the first and last stages (represented by $s = 0$ and $s = 9$) only set scale boundaries and are not part of the scale proper.

Counts of bud stage observations were pooled from data for the three shoot collections from the three orchards. Calculations of p_i were therefore based on data for 105 'Royal Rosa' cuttings (60% of total), 101 'Sundrop' cuttings (60%), and 68 'Trevatt' cuttings (40%). Fewer data were included for 'Trevatt', as bud abscission before petal fall was common on this cultivar. Only cuttings on which buds developed from Stage 0 (dormant) to Stage 9 (pistil expansion) were included to equalize expected counts for each stage over the forcing period. Furthermore, only the final observation of buds at Stage 0 was counted to provide a minimum estimate of the transit duration from the actual start of development to its visible appearance at Stage 1. This step was needed, since Stage 0 (dormant) is an indefinite stage with only one boundary (to Stage 1). A similar procedure is not required for Stage 9 (also indefinite) since calculations included observation data to Stage 8 only.

The adjusted developmental scale was used to describe progression of floral phenophases following budbreak. Bud development was monitored at three commercial orchards in Hawkes Bay, New Zealand, from 30 June to 23 Aug. 1992. During this period mean daily temperature was 9.0 °C and mean daily maxima 15.0 °C. This extended use of the adjusted scale therefore required the assumption that relative developmental rates at different scale stages observed under 20 °C forcing were representative of developmental rates under field conditions (i.e., the relative duration between recognizable stages is independent of temperature).

Population phenophase values numerically equivalent to each integer or adjusted scale stage corresponded to the median developmental stage (i.e., phenophase 7 implies 50% buds at anthesis). Three fractional phenophases were inserted before phenophase 1 (50% bud movement) to increase discrimination during the earliest (and most prolonged) period of budbreak (Table 1). The distribution of bud development near bloom meant phenophase 5 (50% of buds at Stage 5) usually corresponded to 1% anthesis, and phenophase 6 (50% of buds at Stage 6) to 5% anthesis (5% bloom). Ordinary least squares regression (PROC REG: SAS Institute, 1989) was used to fit linear functions of chronological time through the adjusted phenophase data. Confidence intervals for the x-axis intercept were then calculated from regression statistics (Snedecor and Cochran, 1980).

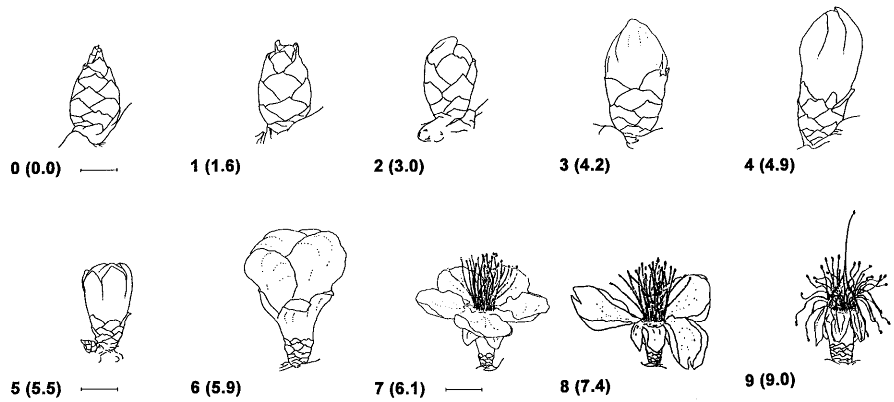

Fig. 1. Flower bud growth stages for 'Royal Rosa', 'Sundrop', and 'Trevatt' apricots, with mean adjusted stage values for all cultivars in parentheses. Stage descriptions: 0—no visible bud growth; 1—separation of bud scales; 2—initial protrusion of sepals; 3—broadening of exposed sepals; 4—expansion and rounding of sepals; 5—initial protrusion of petals; 6—expansion and rounding of petals; 7—presentation of anthers and stigma; 8—abscission of petals; 9—swelling of pistil beyond corolla cup. (Bars = 2.5 mm: stages 0–4; 5 mm: stages 5–6; 10 mm: stages 7–9.)

Table 1. Interpolated fractional population phenophases used during early apricot floral bud break.

	Interpolated phenophases	
Buds at Stage 1	Integer (s)	Adjusted (s')
5–10%	0.25	0.4
10–25%	0.50	0.8
25–50%	0.75	1.2

Results and Discussion

Summations of stage observations of apricot flower buds based on stage definitions produce an unequal distribution of counts over the entire scale, indicating a nonlinear rate of progress through scale stages. More first-moving buds on 'Royal Rosa', 'Sundrop', and 'Trevatt' cuttings forced at 20 °C were recorded at earlier and later stages during the 4-week observation period than at stages describing development before anthesis. Histograms for each cultivar (Fig. 2A) show a steady decrease in observed frequencies from integer Stage 1 (budbreak) to Stage 6 (balloon). Hence, numbers of buds observed at Stages 4, 5, and 6 were lower than expected if transit times for each stage were equal (χ^2 = 390, 16 df, $P <$ 0.001). This reflects slower passage of buds through early developmental stages relative to stages immediately before bloom.

Adjusted scales were individually calculated for each cultivar (Fig. 2B). Relatively slow movement of buds through initial stages meant their numeric values increased when adjusted for the difference between observed and expected frequencies. Adjusted numeric values for later stages were lower than original integer values due to shorter times spent at Stages 5 and 6 than represented by the integer increments of the integer scales. Anthesis, Stage 7 on the integer scale, was therefore represented by Stage 6.0 on the adjusted scale for 'Sundrop', 6.2 for 'Royal Rosa', and 6.3 for 'Trevatt'.

The data from which these individual scales were calculated were then used to derive a common scale (Fig. 1, adjusted scale values) to simplify field application and permit direct phenological comparison between cultivars. Relative frequencies for 'Royal Rosa' and 'Trevatt' did not differ from each other (χ^2 = 12.1, 8 df, NS) but together differed from those of 'Sundrop' (χ^2 = 59.0, 16 df, $P <$ 0.01). This was due to relatively high numbers of 'Sundrop' buds observed at integer Stage 2 compared with corresponding frequencies for 'Royal Rosa' and 'Trevatt'. This may reflect a bias in categorizing buds due to slightly different bud morphology of the three cultivars. Despite this statistical difference, the overall similarity of the histograms was considered sufficient to justify a common scale.

Chronological progression of development was more linear when expressed on the common adjusted scale (Fig. 3). The increased linearity was sufficient in most cases that the fitted regressions provided an efficient and accurate summary of the phenological data. It permitted the detection of small but significant effects of both orchard and cultivar on rate of development (change in developmental stage, s', per unit time) (Table 2). Extrapolation of the linear regression lines to phenophase data could also be used to estimate the start of bud movement (the x-axis intercept), the 95% confidence interval being ±5.5 d. Both features illustrate the usefulness of the scale adjustment technique.

Extrapolated x-axis intercept values must be interpreted very carefully because of possible bias from two sources. Random bias can be introduced into intercept estimates when data points are unevenly spaced, as lines fitted to field observations illustrate (e.g., 'Sundrop' at Fernhill, Fig. 3B). Systematic bias may be even more significant if the adjusted value of the first visible (nonzero) growth stage (which here represents the first sign of bud move-

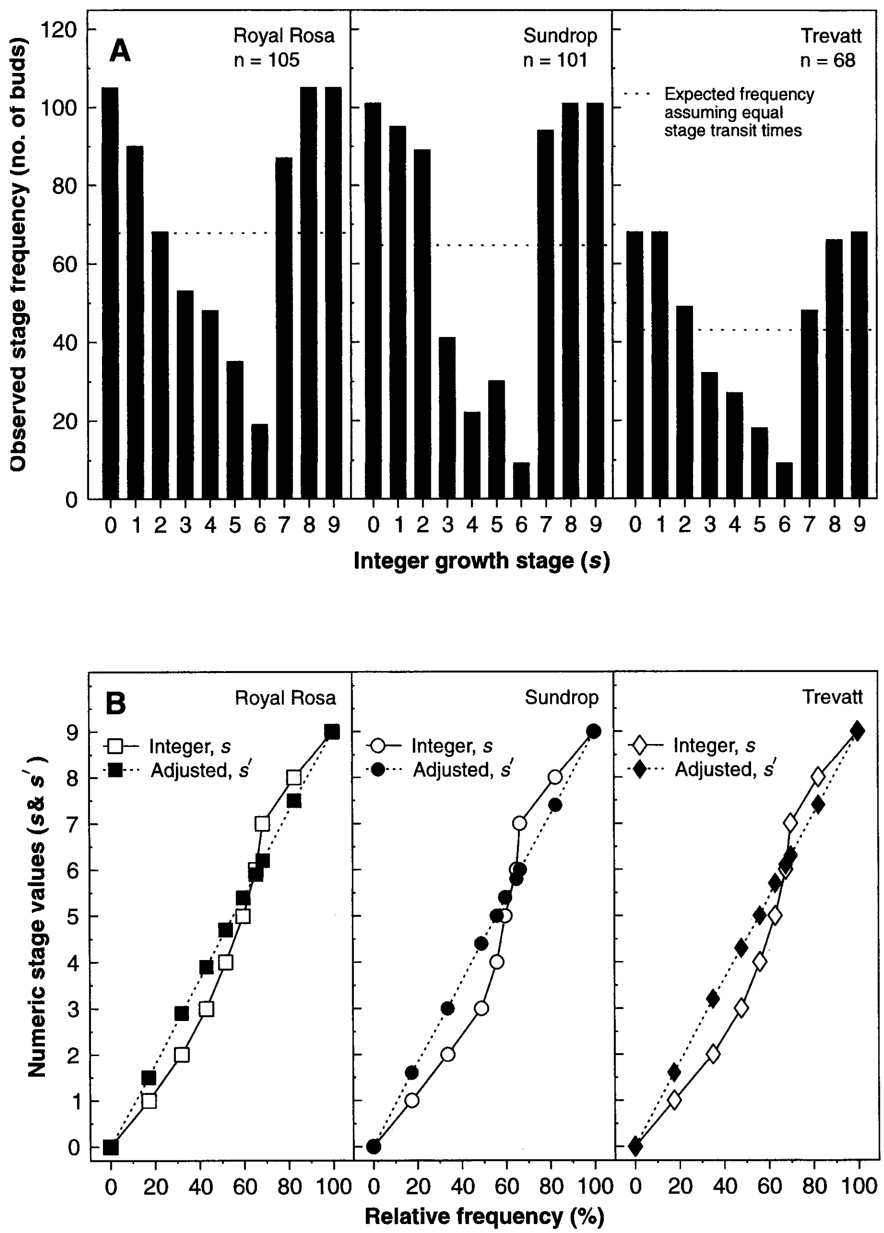

Fig. 2. Histograms for 'Royal Rosa', 'Sundrop', and 'Trevatt' apricot flower bud integer growth stages and corresponding adjusted scale values. (**A**) Counts of bud stage observations for the first-moving buds on cuttings incubated for 4 weeks at 20 °C and assessed twice weekly from Stage 0 (no movement) to Stage 9 (pistil swell). (**B**) Adjusted developmental scale values using the cumulative proportion of bud stage observations.

ment) does not accurately reflect the duration from the actual beginning of bud development. It is important to note that the value given to the initial scale stage is arbitrary since development actually begins from a fixed "zero point." Instead, the original and adjusted scales are continuous in both developmental directions and stage values merely a matter of convenience. In the present case, the adjusted value given to Stage 1 (i.e., 1.6) is a *minimum* estimate of actual developmental duration, determined only by the exclusion of all but the last nonmoving observation for each bud in the original forcing data. If all bud stage observations had been included, then the adjusted value for Stage 1 would have been higher. Extrapolated *x*-axis intercept values therefore represent a *latest* estimate for the start of bud development. Higher adjusted initial stage values would yield *earlier* intercept estimates.

Application of the adjusted scale under field conditions also requires the assumption that the temperature response of developmental rate is uniform over the scale range. Relative stage durations could depend on forcing temperature, particularly if the temperature optimum varies during development. A different adjusted scale could therefore result if buds were forced at a higher or lower temperature. In this example any differences appear likely to be small, as the scale covers only a limited developmental distance (i.e., budbreak to just beyond bloom), but errors due to changing developmental temperature optima could be more significant if the scale was more extensive. Counting bud stage observations at a range of temperatures would test whether developmental temperature optima did actually vary between stages.

The linearity of the adjusted scale with time of development under orchard conditions suggests that stage frequency data derived from budwood forcing at 20 °C did provide a valid basis for adjusting this phenology scale. However, the validity of the adjusted scale may have been assisted by relatively constant temperature conditions in Hawkes Bay throughout the field observation period. Daily air temperature maxima ranged from 10.5 to 17 °C, without marked week-to-week variation, and generally were between 14 °C and 16 °C. Thus, apparent developmental rates, measured in adjusted scale units per day, were relatively constant over the period of observation and explain why use of heat unit accumulations (GDH °C) did not improve linearity further.

Stage value adjustment based on the cumulative proportion of bud stage observations under constant temperature conditions therefore provided an effective method of obtaining a linear relationship between phenological scale values and actual development over the scale range. The method aided analysis of apricot phenology data, particularly calculation of developmental rates and interpolation between known values. The continuous nature of the adjusted scale makes the concept of an "average (mean) stage of development" meaningful, whereas with nominal (or ranked) scales it is more proper to speak only of the median. Counting bud stage observations also provided a simple indirect method of estimating the relative durations of the stages without daily observation. The required manipulation may be performed very simply as part of standard statistical analyses, and the adjustment method appears to be applicable to a variety of phenology scales. This method should also assist phenological modeling by allowing description of development by linear equations, using chronological or thermally weighted time as independent variables.

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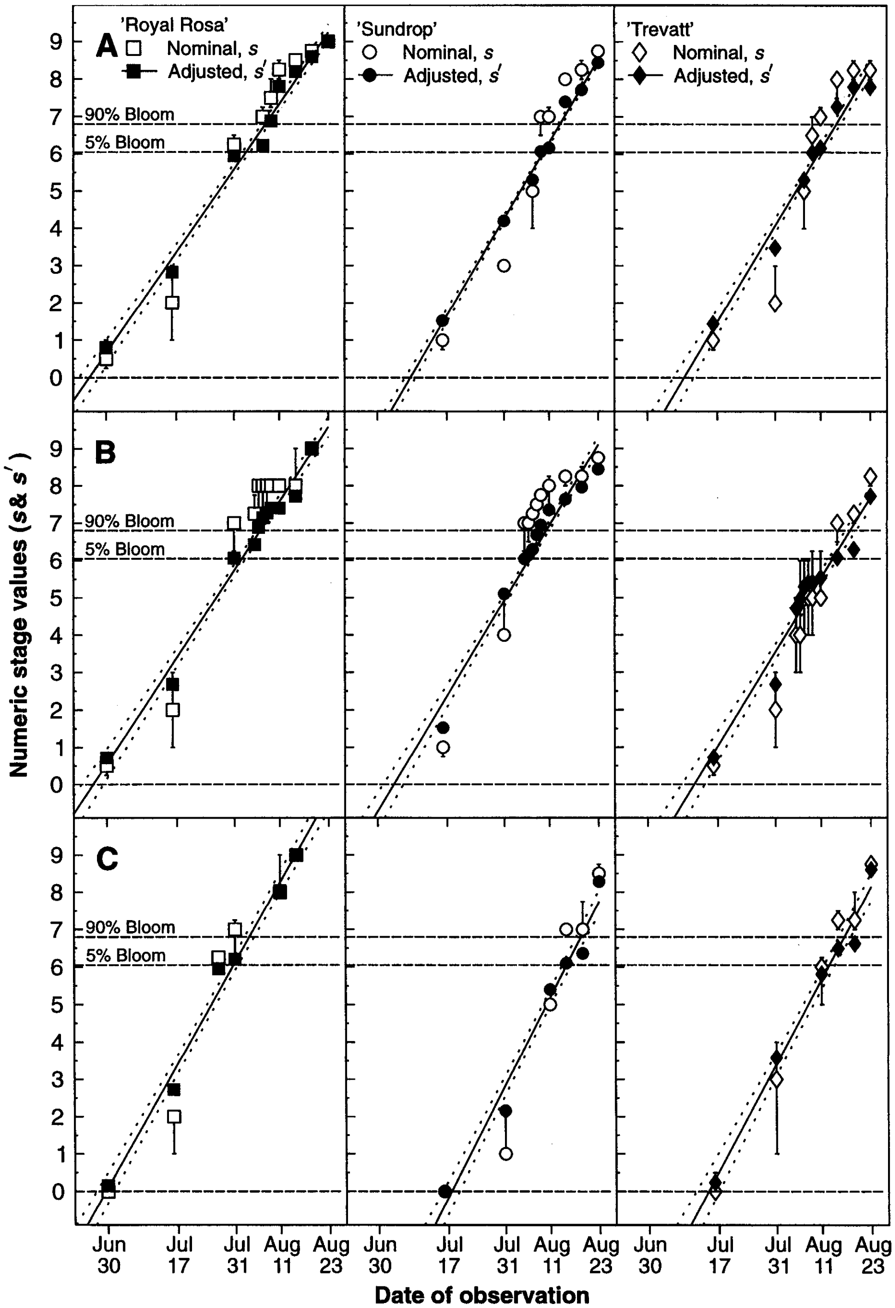

Fig. 3. Comparison of median integer scale observations (s) with mean adjusted stage values (s') and fitted linear regressions as indices for flower bud phenophases on 'Royal Rosa', 'Sundrop', and 'Trevatt' apricot trees at three Hawkes Bay orchards from late June to mid-Aug. 1992. (**A**) Campbell; (**B**) Fernhill; (**C**) Stirling. (Bars represent range of integer scale observations, n = 5).

Table 2. Analysis of variance for effect of orchard and cultivar on flower bud development in 'Royal Rosa', 'Sundrop', and 'Trevatt' apricots at three Hawkes Bay orchards, June to Sept. 1992.

	Chronological days	
Source	df	Type III MS
Model	17	125.1***
Orchard	2	5.2***
Cultivar	2	7.3***
Residual 1: orchard × cultivar	4	0.2^NS
Regression	1	1875.6***
Regression × orchard	2	4.5***
Regression × cultivar	2	2.9***
Regression × orchard × cultivar	4	0.1^NS
Residual 2: error	362	0.3
R^2		0.95

NS, ***Variance components nonsignificant or significant at $P < 0.001$.

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