Predicting Stem Length of Cut Flower Roses at Harvest Using Stem Elongation Rates in Relationship to Developmental Events

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Abstract

Stem length is a major determinant of rose productivity because cut flower roses are graded and marketed by stem length. The ability to predict stem length at harvest could be an advantage for growers for forecasting crop pricing and potential cash flow. Management decisions that optimize stem length could be made by monitoring stem elongation during a growth cycle. For example, if stem lengths are shorter than expected, management decisions could be made to remedy salinity, irrigation, nutrition problems, or greenhouse air temperature. The objective of this project was to determine how stem elongation of roses was related to discrete developmental events during a growth cycle and to develop and test methods for predicting stem length at harvest. The length of stems of greenhouse-grown rose plants was measured daily, along with the number of unfolded leaves on those shoots. The dates of bud break, visible bud, and harvest were also recorded. Data on relative stem elongation versus relative time since bud break were fit to a Richards function using nonlinear regression. The Richards function was used to calculate the percent of final stem height that should be achieved at each leaf unfolding event and thus predict stem length at harvest given current stem length. This method showed on average a twenty percent error in predicted harvest length when early leaf unfolding events were used and error decreased to seven percent when the later leaf unfolding events were used. The predictive models were calibrated using data from three growth cycles during summer and fall seasons. In a separate validation data set from a spring growth cycle the model was biased toward overpredicting final stem height, suggesting that the model must be calibrated for specific varieties and growing conditions. Overall, the model provides a useful method for predicting final stem length with increased accuracy the later in the growth cycle these measurements were taken.

INTRODUCTION

Stem length is a major determinant of cut flower rose productivity and quality since rose flowers are graded and marketed based on stem lengths. The ability for growers to predict stem lengths could be used in planning marketing and in greenhouse energy management.

Stem elongation of rose stems occurs in a sigmoidal pattern from bud break to harvest over a typically 4-6 week growth cycle in a greenhouse. This pattern can be separated into three phases: exponential, linear, and ripening or senescence (Goudriaan and Van Laar, 1994). Stem elongation rate is accelerating during the exponential phase, constant but relatively rapid during the linear phase, and decelerating during the ripening phase. Previous researchers have used logistic or Richards functions (Richards, 1959) to fit stem length or plant height over time during production cycles of chrysanthemum (Karlsson and Heins, 1994; Lieth and Larsen, 1993), poinsettia (Fisher et al., 1996), and roses (Hopper, 2000). The Richards function is often used in modeling sigmoidal growth patterns such as stem elongation (as above), increases in leaf surface area (Cromer et al., 1993), and plant biomass accumulation (Camara-Zapata et al., 2003). The Richards function takes the form:

$$y(t) = \frac{Ab}{(A^n + (b^n - A^n)e^{-kt})^{1/n}} \tag{1}$$

where t and y are the independent and dependent variables, respectively, and there are four parameters: A, b, k, and n.

The objective of this experiment was to determine how stem elongation of roses was related to discrete developmental events (leaf unfolding) during a growth cycle and to develop a method for predicting stem length at harvest based on fitting stem length versus time to a Richards function.

MATERIALS AND METHODS

Rosa hybrida L. 'Kardinal' plants were planted in May 1997 and grown in greenhouses at the University of California, Davis (38.5°N latitude). The plants were grown in 8 L square or cylindrical pots in coconut coir. An automated irrigation system controlled based on substrate moisture tension (Lieth and Burger, 1989) was used to provide the plants with a modified half-strength Hoagland's solution (Hoagland and Arnon, 1950). Greenhouse temperature control set points were 24°C day and 17°C night.

The lengths of at least ten stems of plants growing in the greenhouse were measured as close to midday as possible with a ruler. The measurements of a stem were made from bud break (BB, when the shoot reached 1 cm) until three days past the harvestable stage (HV, when a sepal reflexed more than 90° with respect to the longitudinal axis of the shoot). The date that each new leaf unfolded was recorded. "Leaf unfolding" was defined to have occurred when the midrib of the terminal leaflet was visible adaxially (L_1 refers to unfolding of lowest/oldest leaf on the stem, L_2 the second to lowest, etc.). Three sets of data were collected at different times of the year. From 5 Sep through 3 Oct, 2000, ten stems were measured; from 30 Sep through 9 Nov, 2000, ten stems were measured; and from 5 Jun through 10 Aug, 2001, eleven stems were measured.

For each growth cycle, relative stem length measurements were fit to a Richards function (Fig. 1). In this analysis individual data points were plotted using relative time since bud break (calculated as number of days since bud break divided by total number of days from bud break to harvest) as the independent variable; and relative stem length (calculated as current stem length divided by stem length at harvest) as the dependent variable. Nonlinear regression was conducted with Statistical Analysis System (SAS, function NLIN) to determine best fit parameters for the Richards function. The parameters were determined for each growth cycle separately and for the three cycles grouped together (Table 1).

The relative time for each leaf unfolding event (L_N) was calculated similar to above as the number of days from bud break that the L_N occurred divided by the total number of days from bud break to harvest. Mean relative time for each leaf unfolding event was calculated for each growth cycle. In this way we could determine relative time in the growth cycle using leaf unfolding as easily observable discrete developmental events.

To predict stem length at harvest, the Richards function parameters for relative stem length versus relative time were used. Using the Richards function, the percentage of final height that should be achieved at each L_N can be calculated. Predicted height at harvest was then calculated at each L_N using current height (in cm) divided by percent of final height at that relative time as in equation 2.

$$\textit{predicted height at harvest} = \textit{height at } L_N \,/\, \frac{Ab}{(A^n + (b^n - A^n)e^{-k(\textit{rel time } L_N)})^{1/n}} \tag{2}$$

Predicted stem length at harvest was calculated for each flower stem using the parameter values from Table 1 (pooled across the three cycles) and relative time for each L_N (Fig. 2).

A validation data set was obtained from seven-year-old 'Kardinal' rose plants in spring 2005 from 2 April through 15 May, 2006. The plants were grown in sixteen L square pots in coconut coir with two plants per pot. An automated irrigation system provided the plants with a modified half-strength Hoagland's solution (Hoagland and Arnon, 1950) three times daily. Plants received ambient CO_2. Greenhouse temperature control set points were 24°C day and 16°C night. The actual mean daily temperature and light integral were 23.9°C and 26 $mol \cdot m^{-2} d^{-1}$ PAR. As above, daily stem length measurements and developmental event observations were recorded.

RESULTS

Relative time for each L_N did not differ significantly across crop cycles with the exception of L_{10} and L_{11} (Fig. 2). Relative time for L_{10} in cycle 2 was significantly less than in cycle 1; and relative time for L_{11} in cycle 2 was significantly less than in cycles 1 and 3. Overall, there was little variation in relative time across the cycles, therefore mean relative time across the three cycles was used in the model to relate relative time to each L_N.

Stem heights at harvest were predicted for each L_N for the thirty-one stems in cycles 1-3. Predicted harvest lengths were calculated at each L_N and compared with measured length at harvest. On average, predicted harvest stem lengths at L_1 were ± twenty percent of measured stem length at harvest with variation decreasing to ± seven percent when predictions were made at L_{12}-L_{14} (Fig. 3).

At harvest, measured stem lengths varied from 40 to 80 cm which indicates the variation in stem quality present between individual stems and plants (Fig. 4). There was a relatively weak linear relationship between predicted and measured stem height when predictions were made at early leaf unfolding events (Fig. 4a and 5). The relationship between predicted and measured height became stronger as predictions were made later in the growth cycles (Fig. 4b and 5). For example R^2 for predicted versus measured stem height increased from 0.29 at L_2 to 0.88 at L_{12} (Fig. 4). There was little bias in under- versus overprediction at L_{12} as the linear relationship between predicted and measured height had a slope of 1.07.

For the validation data set, predictions made at early leaf unfolding events (L_1-L_3) were biased toward underprediction, while predictions made at later leaf unfolding events (L_5-L_{12}) were biased toward overpredicting stem height at harvest (Fig. 6a). There was a strong relationship between predicted and measured height for later leaf unfolding events. For example, the R^2 for predicted versus measured height at L_{10} was 0.89 (Fig. 6b). However, there was a bias toward overpredicting stem height for longer stems as the slope of predicted versus measured height was 1.46.

DISCUSSION

The transformed data (i.e. data in terms of relative time and stem length) do follow a sigmoidal pattern as in the Richards function with excellent fit (R^2=0.91), suggesting its usefulness in modeling stem elongation rates in roses (Fig. 1).

There is some variation in relative time for each leaf unfolding event (Fig. 2). In using equation 2 to predict stem heights, this variation in relative time since bud break represents variation in the independent variable and ultimately decreases the accuracy of predicted stem height at harvest.

For any one individual stem, there is a fairly large error rate in the predictive model (Fig. 3 along with Fig. 4 and 5). However if a representative set of stems are used, the model does a reasonable job of predicting final stem heights (mean percent difference was about ± 20 percent early in the cycle and decreases to about ± 5 percent later in the cycle). Overall, by monitoring a representative set of stems, a grower can use this information for a reasonable estimate of the stem lengths at harvest.

The validation data set (Fig. 6) shows some of the same trends as in the calibration data set, such as increasing accuracy with later leaf unfolding events. But, it also shows greater bias in predictions. The bias is toward underpredictions for early events and overpredictions at later leaf unfolding events. It was noted that stems in the validation data set tended to be weaker (smaller in diameter and shorter) than those in the calibration data set. One-third of the stems in the validation data set had more than 10 nodes and two-thirds of the stems in the calibration data set had more than 10 nodes. Increased greenhouse air temperatures are known to reduce stem length of roses (Yamaguchi and Hirata, 1998). Differences in temperature between the calibration (actual temperature not available) and validation data sets may also explain differences in stem quality and model predictions.

The relative time for leaf unfolding events of the stems used for validation may have differed significantly from those used in calibration. For example, early (older) leaves of the validation stems might unfold earlier in relative time compared to those leaves of the calibration stems and would explain underpredictions of length for younger stems. Conversely, later (younger) leaves might unfold later in relative time compared to the leaves on the stems used for calibration and would explain overpredictions of older flower stems.

Overall, this may mean the model needs to be calibrated when used for different varieties and different growing conditions. Perhaps the roses in the validation data set had greater media salinity (not measured) causing the weaker stems. Including other stem characteristics, such as diameter, may lead to more accurate predictions.

Although the predictions become more accurate later in the crop cycle, the model can still be useful. The model provides good predictions at L_{10}, which is also near the visible bud stage. At this point, the crop still has 46% of the development time remaining until harvest. For example, this would be 16 days prior to harvest of a 35 day crop. When we calculate the relative length at this time point, stems would have completed 58.8% of their elongation. Therefore, we can determine that the height at harvest should be 1.70 times (1.70 = 1/0.588) the length at L_{10}. Developing calibration tables of this parameter for other rose varieties would make it easy for growers to adopt this method as a tool to predict stem lengths at harvest. For example, a ruler could be developed to grade flower stems at a given stage, such as L_{10}. The ruler could be used in deciding if a particular flower stem is of inferior quality and should be bent for photosynthesis or pruned out, or if the stem should be left to be harvested. The ruler could also be used in economic forecasts by measuring several stems at L_{10} to gain information on the flower grade distribution that can be expected from the crop at harvest.

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<u>Tables</u>

Table 1. Calculated parameter values for data on relative stem length (dependent variable) versus relative time since bud break (independent variable) fit to a Richards function using nonlinear regression in Statistical Analysis System.

Parameter	Calculated parameter values			
	Cycle 1 (Jun 5 – Aug 10)	Cycle 2 (Sep 5 – Oct 3)	Cycle 3 (Sep 30 – Nov 9)	Cycles combined
A	0.0324	0.0341	0.0255	0.0309
b	1.0045	1.0458	1.0408	1.0278
n	1.4183	0.9626	0.9445	1.1377
k	8.9989	6.6963	7.0092	7.5701
R^2	0.86	0.91	0.96	0.91

Figures

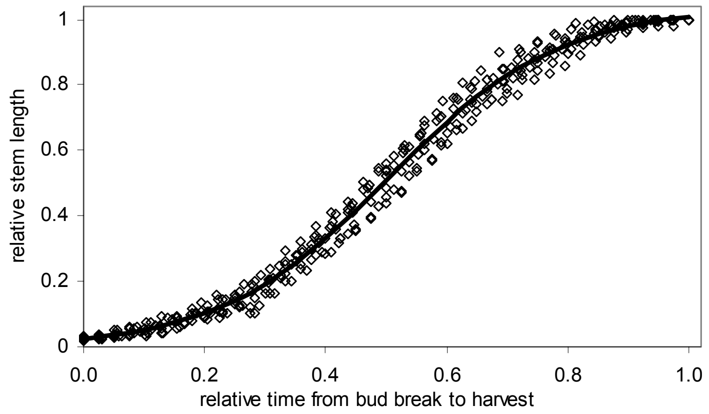

Fig. 1. Richards function fit to transformed stem data, i.e. relative stem length versus relative time since bud break. Data represent 10 stems measured during cycle 2.

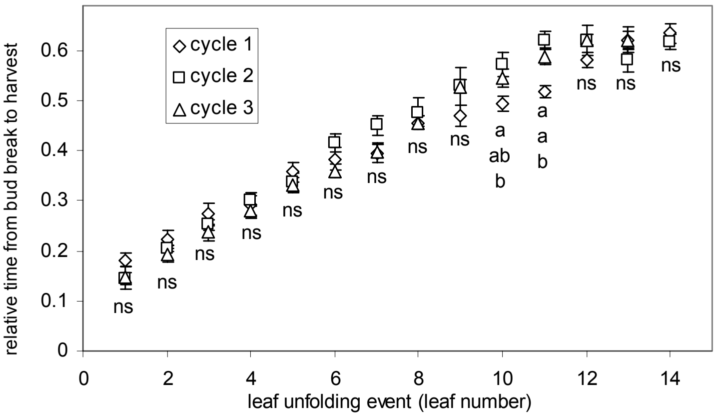

Fig. 2. Relative time since bud break for each leaf unfolding event. Data represent means (± SE) for each leaf event for each cycle. Letters denote mean separation comparisons for each leaf event across cycle utilizing Tukey's HSD (*P*=0.05).

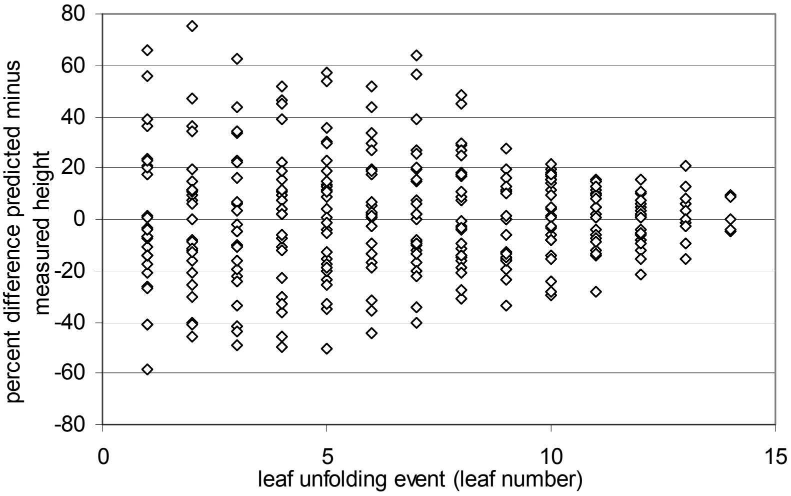

Fig. 3. Percent difference between predicted height and measured height. Data points represent predicted height at each leaf unfolding event for each stem from the three cycles grouped together.

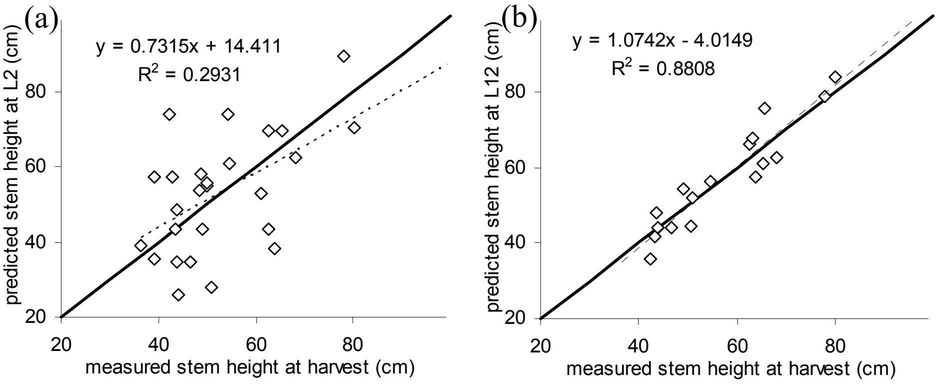

Fig. 4. Predicted stem height at unfolding of leaf 2 (a) and 12 (b) versus measured stem height. Data points represent stems from the three cycles. The dashed line represents the equation for the linear relationship between predicted and measured height and the solid line represents y=x.

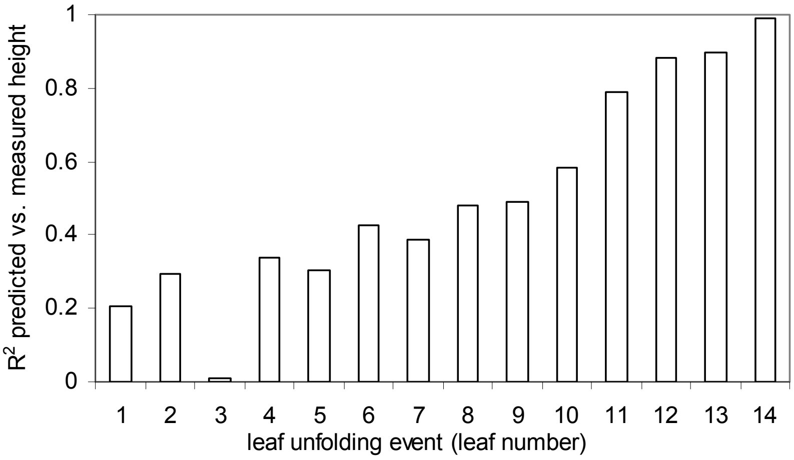

Fig. 5. R^2 values for the linear relationship of predicted versus measured stem height at each of the leaf unfolding events.

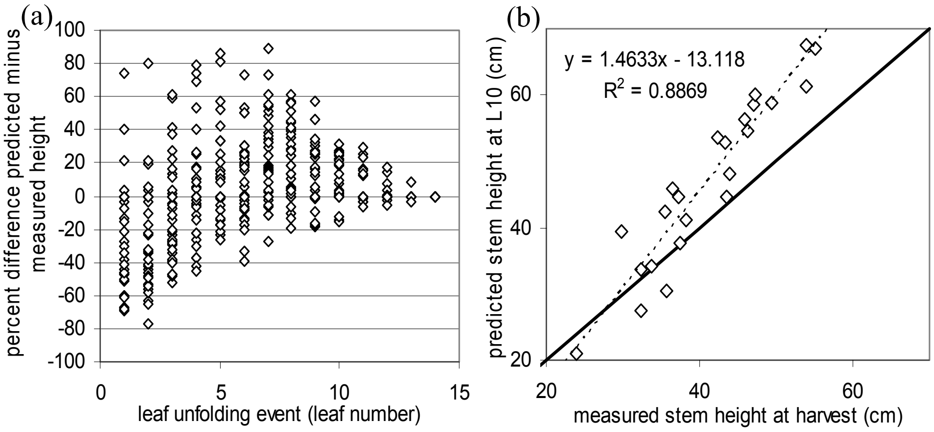

Fig. 6. Percent difference between predicted height and measured height (a) and predicted stem height at unfolding of leaf ten versus measured height at harvest (b). Data points represent thirty-six ‘Kardinal’ stems from the validation data set. The dashed line represents the equation for the linear relationship between predicted and measured height and the solid line represents y=x.