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Estimation of Shoot Development for a Single-stemmed Rose 'Vital' Based on Thermal Units in a Plant Factory System

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Abstract. This study was conducted to predict number and fresh weight of leaves, and total leaf area of a single-stemmed rose 'Vital' based on the accumulated thermal units, and to develop a model of shoot development for the prediction of the time when the flowering shoot reaches a phenological stage in a plant factory system. The base temperature (T_b), optimum temperature (T_{opt}), and maximum temperature (T_{max}) were estimated by regressing the rate of shoot development against the temperature gradient. The rate of shoot development (R, d^{-1}) for the phase from cutting to bud break (CT-BB) was best described by a linear model R_b (d^{-1}) = $-0.0089 + 0.0016 \cdot temp$. The rate of shoot development for the phase from bud break to harvest (BB-HV) was fitted to the parabolic model R_h (d^{-1}) = $-0.0001 \cdot temp^2 + 0.0054 \cdot temp - 0.0484$. The T_b, T_{opt}, and T_{max} values were 5.56, 27.0, and 42.7℃, respectively. The T_b value was used in the thermal unit computations for the shoot development. Number of leaves, leaf area (LA), and leaf fresh weight showed sigmoidal curves regardless of the cut time. The shoot development and leaf area model was described as a sigmoidal function using thermal units. Leaf area was described as $LA = 578.7\ [1 + (\text{thermal units}/956.1)^{-8.54}]^{-1}$. Estimated and observed shoot length and leaf fresh weight showed a reasonably good fit with 1.060 ($R^2 = 0.976^{***}$) and 1.043 ($R^2 = 0.955^{***}$), respectively. The average thermal units required from cutting to transplant and from transplant to harvest stages were 426 ± 42℃·d and 783 ± 24℃·d, respectively.

Additional key words**:** base temperature, growth model, leaf area, single-node cutting, sigmoidal function

Introduction

A plant factory is an empirical, new production system that maximizes crop production in environmentally friendly facilities through automation and complex environmental control systems. For cut rose production, the factory system can produce a massive uniform quality of cut flower roses per unit area in short cultivation cycles using the self-rooted, single-stemmed roses raised from single-node cuttings (SNCs) with a five-leaflet leaf (Bredmose and Hansen, 1996; de Vries, 1993). The growth and development of crop plants is strongly dependent on environmental factors such as photoperiod, radiation, temperature, and CO_2 concentration. The commercial cultivars of roses are self-inductive, so every shoot has the potential to form a flower regardless of the photoperiod and irradiance level (Halevy, 1984; Pasian and Lieth, 1994). Temperature has been shown to influence both the rate of dry matter accumulation and shoot development in rose production (Pasian and Lieth, 1994). Temperature is the primary variable used in model and among the most important environmental factors to predict the rates of plant development, growth, and yield. Accumulation of heat during the growing season is required to provide enough energy for the organism to move to the next developmental stage. A common approach for expressing the relationship between temperature and plant development is to calculate thermal units, also known as heat units or degree days, required between two development stages (McMaster and Wilhelm, 1997; NeSmith, 1997). A thermal unit model, which embraces the concept of thermal units, has been described as the timing of biological processes (McMaster and Wilhelm, 1997) and the prediction of growth and yield (NeSmith, 1997; Tei et al., 1996; Yin and Kropff, 1996). The thermal time for the developmental periods could be calculated using the base temperature (T_b) below, in which metabolic processes and development do not occur (Thornley and Johnson, 1990). The T_b (base temperature) values have been determined experimentally and differ across plant species, cultivars, and developmental stages (Pasian and Lieth, 1994).

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Pasian and Lieth (1994) reported that the base temperature estimate for the growth period from bud break to harvest was 5.2℃ for the rose Cara Mia and that the duration of the period from the bud break to either the appearance of the visible bud or harvest could be reasonably well predicted.

It has been shown that leaf emergencies or the unfolding of each leaf are highly correlated with the accumulated thermal units (Craufurd et al., 1998; NeSmith, 1997; Qi et al., 1999; Pasian and Lieth, 1994). The leaf area is an important determinant of light interception, photosynthesis, water and nutrient use, crop growth, and yield potential (Marcelis et al., 1998). The leaf area development is predominantly simulated as a function of the plant's developmental stage (often determined by the heat sum) or of the estimated dry leaf weight multiplied by the specific leaf area (SLA) (Lieth and Pasian, 1991; Marcelis et al., 1998). Although mathematical simulation of the leaf area has been used for several plants, such as for roses (Lieth and Pasian, 1991), tomatoes (Cho and Son, 2005; Heuvelink, 1999), and chrysanthemums (Lee and Heuvelink, 2003), no such model exists for single stemmed roses.

The objectives of this study were: (1) to predict the total leaf area, number of leaves, and fresh leaf weight of the single stemmed rose 'Vital' based on the thermal time in a plant factory system, and (2) to develop a model of shoot development for the prediction of the time at which the flowering rose shoot reaches the phenological stage, e.g., cutting, bud break, and harvest.

Materials and Methods

Plant materials and environmental conditions

Four experiments with different cutting dates were conducted in a year, in a Venlo-type plant factory installed with supplemental lighting of PAR about 300 $\mu mol \cdot m^{-2} \cdot s^{-1}$ using a high-pressure sodium lamp. The cutting dates were 20 October (Exp. 1) and 29 November (Exp. 2) in 2004, and 8 April (Exp. 3) and 1 June (Exp. 4) in 2005. The plants cut on 20 October, 2004 and 8 April, 2005 were used to develop the growth models. The plants cut on 29 November, 2004 and 1 June, 2005 were used to validate the models.

The large flowered rose 'Vital', which is an appropriate cultivar for a plant factory due to its high shoot growth rates (Yeo and Lee, 2009), was used in the experiment. SNCs with one five-leaflet leaf that had undeveloped auxiliary buds were excised from a flowering stem. The prepared cuttings were planted in sufficiently saturated rookwool cubes (7.5 × 7.5 × 6.5 cm, UR Rockwool, Korea) after the basal part of each scion was treated with a commercial rooting powder that contained auxin (Rootone, Union Carbide, USA). The relative humidity was kept above 90% during the cutting, using mist from the cutting to the rooting.

The actual environmental conditions were monitored with sensors and continually recorded with data loggers located inside the greenhouse. The air temperature in the plant factory was measured with T-type thermocouples every 10 minutes using a data logger (CR10X, Campbell Scientific, Logan, Utah, USA). The set point temperatures for heating and ventilation were 15 and 29℃, respectively. The photosynthetically active radiation (PAR, $\mu mol \cdot m^{-2} \cdot s^{-1}$) inside the plant factory varied naturally over the experiment period, and was measured every 15 minutes using quantum sensors (LI-190SA, LI-COR, Lincoln, USA) located at the top of the flowering shoot canopies. The daily PAR integral ($MJ \cdot m^{-2} \cdot d^{-1}$) was calculated from quarter-hourly PAR averages.

Nutrient solution

Before the formation of a callus, tap water was supplied to the cuttings on the Ebb & Flow system. The rooted cuttings were fed with the nutrient solution for SNCs developed by the University of Seoul (UOS). The UOS solution provided the following nutrient concentrations during the rooting stages: for the macronutrients ($me \cdot L^{-1}$), 8.8 NO_3-N, 0.67 NH_4-N, 2.0 P, 4.8 K, 4.0 Ca, 2.0 Mg, and 2.0 SO_4-S; and for the micronutrients ($mg \cdot L^{-1}$), 1.5 Fe, 0.35 B, 0.58 Mn, 0.35 Zn, 0.045 Cu, and 0.045 Mo. The nutrient solution was supplied to SNCs 10-13 times a day using an automatic irrigation system based on a timer, with compensation of the pH to maintain a level of 5.8-6.0. The electrical conductivity (EC) of the solution was gradually increased from 0.5 to 1.5 $dS \cdot m^{-1}$

Table 1. Target values of mineral elements in the root environment of single-stemmed rose 'Vital' grown in an experimental plant factory.

Macroelement ($mg \cdot L^{-1}$)					
NO_3-N	NH_4-N	P	K	Ca	Mg
100-150	<10	30-50	100-150	80-120	20-80
Microelement ($mg \cdot L^{-1}$)					
Fe	Mn	Zn	Cu		
1.5-3.0	0.2-0.6	0.2-0.5	0.03-0.10		

for the nutrient management of the rooted cuttings.

The SNCs were transplanted into a closed aeroponic system after two true leaves appeared. The plants were grown at a plant density of 7.5 × 15 cm^2, between-row × within-row (89 plants/m^2). The nutrient solution was analyzed at intervals of 7 days after transplant. The composition of the mineral ions in the nutrient solution was regulated to maintain constant concentration levels, by supplementing each lacking mineral ion with fertilizers, as compared with the appropriate content levels of mineral ions in the root environment (Table 1). These levels were established from the results of a previous experiment (Yeo and Lee, 2009) that determined the optimum nutrient levels for single-stemmed roses in a closed system. The pH was measured every 3 days with a pH meter (pH-93, Aalsmeer-Holland, Netherlands) and adjusted to the 5.8-6.0 level with KOH and H_2SO_4.

Measurements

Destructive measurements of single-stemmed roses were carried out every 3 to 7 days until the final harvest. Samples were taken from 10-20 plants per experimental plot, excluding border plants in two rows on each side of a bed. The length of the cut flowers, the leaf area, the leaf number, the stem diameter, the flower diameter, and the fresh weight and dry weight (dried at 75℃ for 48 hr in a ventilated oven) of each part of the shoot were determined. Blind shoots were eliminated in the data analysis. Leaves that were beginning to unfold with a leaf area of 1 cm^2 or greater were counted every week. The total leaf area of each plant was measured using a leaf area meter (LI-3100, LI-COR, USA). The photosynthetic leaf characteristics of the single-stemmed roses were also measured. Photosynthesis was measured on the fifth leaflet of the fifth leaf using a potable photosynthesis system (LI-6400, LI-COR, USA).

Base temperature

All biological processes respond to temperature, and all responses can be summarized in terms of three cardinal temperatures: base (T_b) (or minimum (T_{min})), optimum (T_{opt}), and maximum (T_{max}) temperatures (Yan and Hunt, 1999). Before the thermal units could be computed, it was necessary to determine a suitable base temperature (T_b). The base, optimum, and maximum temperatures were estimated by regressing the inverse of the time to the bud break from the cutting and to the harvest from the bud break against the temperature gradient. The estimated value was obtained through extrapolation to the intercept with the abscissa.

The mean rate of flower development during a cultivation period can be denoted as (Larsen and Persson, 1999):

$$\textit{Rate of development}\ (d^{-1}) = 1/d, \qquad (1)$$

in which d is the number of days needed from cut to bud break or from bud break to harvest. The inverse of the parameters were fitted to the linear function and the parabolic function, respectively. The rates of development, R_b (d^{-1}), that reflected the fractional amount of development per day, were related to the daily average air temperature. The rate of development for the phase from cutting to bud break (CT-BB) was computed as follows:

$$R_b\ (d^{-1}) = b + a \cdot \mathrm{Temp}, \qquad (2)$$

in which a and b are the regression coefficients and intercept, respectively. The temperature-axis intercept of this equation is the negative ratio of the parameters b (d^{-1}) and a (℃$^{-1} \cdot d^{-1}$), and is the base temperature, which is computed as follows:

$$T_b = -\ b/a. \qquad (3)$$

The rate of development for the phase from bud break to harvest (BB-HV) stage was computed as follows:

$$R_h\ (d^{-1}) = c + b \cdot \mathrm{Temp} + a \cdot \mathrm{Temp}^2 \text{ and} \qquad (4)$$

$$T_{max} = (-b - \sqrt{b^2-4ac})/2a,\ T_{min} = (-b + \sqrt{b^2-4ac})/2a,\ T_{opt} = -b/2a, \qquad (5)$$

in which c, b, and a are the intercept and the first- and second-order regression coefficients, respectively.

Thermal unit calculation

The thermal time has been used to track the development of agronomic crops and calculated as the mean temperature minus the base or threshold temperature below which no development take place (Wang, 1960). The method applied in this study involves the computation of thermal units (TUs, ℃·d) from the air temperature averages (T_{ave}) in quarter-hourly periods. The thermal time was calculated using the following formula:

$$\mathrm{TUs}\ (℃ \cdot d) = \sum (T_{ave} - T_b), \qquad (6)$$

in which T_{ave} is the daily average air temperature and T_b is the base temperature (℃). The thermal units that were accumulated during the CT-BB and BB-HV stages were calculated using Eq. (6), and phenological observations were performed on a population of 200-300 shoots per experiment. The abbreviations and definitions of rose shoot developmental events are presented in Table 2.

Table 2. Descriptions of event of rose shoot developmental.

Symbol	Description (definition)^z of event
CT	Cutting of stem which leads to the bud break at the node below the cut: The starting point for development of a shoot.
BB	Bud break: Date on which a growing bud reaches a length of at least 10 mm.
TP	Transplant: Rooted cuttings are transplanted when 2-3 true leaves develop.
HV	Shoot becomes harvestable: Date on which the flower buds begin to open, i.e. when the sepal has reflexed and the petal starts to unfurl.

^{z}Based on the work from Pasian and Lieth (1994).

Prediction of shoot development

The number of leaves (NL), leaf area (LA), and fresh leaf weight (FLW) were modeled using the sigmoidal function (Cho and Son, 2007), as follows:

$$Y = M\ [1 + (TUs/a)^{b}]^{-1}, \qquad (7)$$

in which Y is NL, LA, or FLW; M is the maximum potential NL, LA, or FLW; and a and b are constants. A non-linear relationship between LA and NL and between LA and FLW was obtained. The regressive equations are as follows:

$$LA\ (cm^2) = a \cdot e^{b \cdot NL} \text{ and} \qquad (8)$$

$$LA\ (cm^2) = M\ [1 + (FLW/a)^{b}]^{-1}, \qquad (9)$$

in which M is the maximum potential LA, and a and b are constants. The parameters were estimated using the Gauss-Newton algorithm, a non-linear least square technique (Release 8.01, SAS Institute, Inc., Cary, N.C.). The estimated leaf area was compared with the measured one.

Statistical analysis

A completely randomized block experimental design was used. All the data were analyzed using the Statistical Analysis System (Release 8.01, SAS Institute, Inc., Cary, N.C.). The experimental results were subjected to an analysis of variance. The phenological observations of 10-20 plants per experimental plot were used as data for the development and validation of models. The statistical computation of the regression was carried out using the SAS REG procedures and Sigma Plot (SPSS, Inc., Korea).

Results and discussion

Base Temperature

The four cutting dates provided various thermal and radiation regimes from which the data for model development could be gathered. The daily average temperature ranged from 17℃ to 32℃, and the daily PAR integral ranged from 0.2 to 10 $MJ \cdot m^{-2} \cdot d^{-1}$ throughout the experiment (data not shown). Because of high irradiance and high outside temperature in summer, differences in the daily average temperature in the experiments were sometimes higher than desired. The relationship between the rate of rose shoot development (d^{-1}) for different growth phases and the average temperature at which the single-stemmed roses were grown was investigated to obtain the base temperature necessary to develop a thermal unit model (Fig. 1). The base, optimum, and maximum tem-

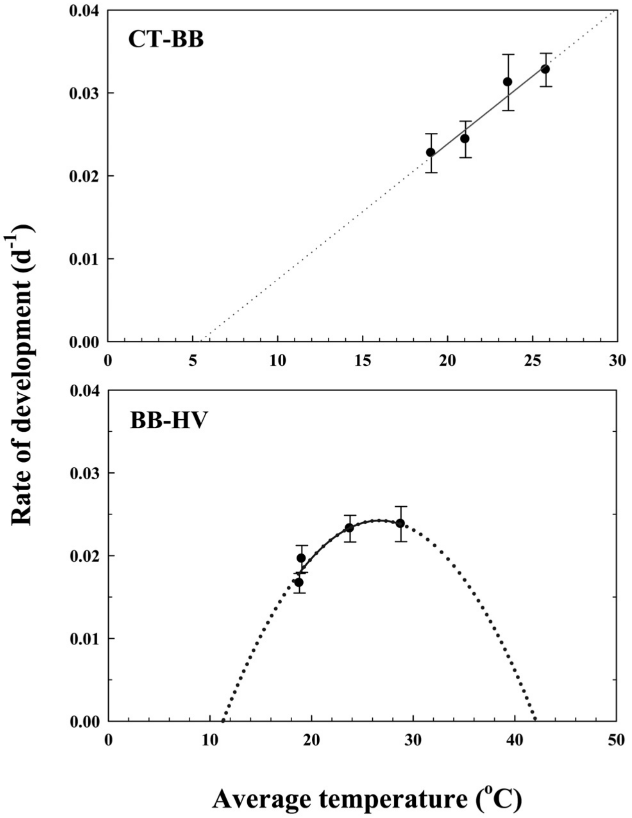

Fig. 1. Linear (CT-BB) and parabolic (BB-HV) models of the rate of development (d^{-1}), the inverse of the time to bud break from cutting (CT-BB) and to harvest from bud break (BB-HV) against the temperature gradient for a single-stemmed rose 'Vital' in a plant factory. Estimated equation were $R_b = -0.0089 + 0.0016 \cdot temp$ ($R^2 = 0.953$) and $R_h = -0.0484 + 0.0054 \cdot temp - 0.0001 \cdot temp^2$ ($R^2 = 0.901$), respectively. Vertical bars indicate the standard errors of the mean values.

peratures were estimated by regressing the rate of development (d^{-1}) against the temperature gradient. The rate of development for the CT-BB, the inverse of the time to bud break from cutting, showed a linear relationship with temperature. The rate of rose shoot development for the CT-BB period was best described by the linear model $R_b = -0.0089 + 0.0016 \cdot Temp.$ (Fig. 1). Accurate summarization of temperature response is a prerequisite to successful modeling of crop systems and application of models to management (Hunt et al., 2001). A linear model of temperature on the rate of plant development is convenient and effective when the temperature does not approach or exceed the optimum, T_{opt} (Summerfield and Roberts, 1987). Temperatures, however, frequently approach and exceed T_{opt} in natural conditions. To accommodate this situation, many researchers have adopted a non-linear approach. In the work of Craufurd et al. (1998), estimates of T_{max} ranged from 36.8 ℃ to 58.9℃ for the leaf appearance rate, with the exception of one genotype, in which a value of 198℃ was obtained, obviously an overestimation.

The rate of development in the BB-HV stage was fitted to the parabolic model $R_h = a + b \cdot Temp. + c \cdot Temp.^2$, in which a, b, and c are the intercept (-0.0484) and the first-order (0.0054) and second-order (-0.0001) regression coefficients, respectively. The temperature-axis intercept of Eq. (2) is the negative ratio of the parameters a (℃-1·d^{-1}) and b (d^{-1}), and is the base temperature. The base temperature of the single-stemmed rose ‘Vital’, which was needed to compute the thermal units, was 5.56℃, which is considerably lower than the minimum temperature recommended for roses grown in greenhouses (16-18℃). This value was used in the thermal unit computations for rose shoot development. Pasian and Lieth (1996) reported that the base temperature estimate for the entire developmental period was 5.2℃ for the rose cultivars ‘Cara Mia’, ‘Royalty’, and ‘Sonia’. In this study, the average air temperatures were monitored continuously and used to compute the accumulated thermal units for each developmental stage. The duration from the bud break to either the appearance of a bud or harvest could be reasonably well predicted (Pasian and Lieth, 1994). Since the x-intercept method of determining the base temperature represents an extrapolation that is far from the mean and even from the closest observed data point (the lowest rate of development at the lowest measured temperature), it is very sensitive to the addition or removal of even a few data points and to variability of the data (Pasian and Lieth, 1994). For temperate species, the base temperature values range from 0 to 5℃ compared with 10 to 14℃ for tropical crops (Monteith, 1981; Moot, 2000; Perry and Wehner, 1986). The base temperature at which metabolic activity ceases varies extensively across plant species. The base temperature of 5.56℃ for rose shoot development means that at that temperature, there is no further development.

Extrapolations of the quadratic function shown in Eq. (4) to the abscissa gave the minimum and maximum temperatures during the BB-HV phase. The minimum and maximum temperatures in the BB-HV growth period were calculated as 11.3℃ and 42.7℃, using Eq. (5). The optimum temperature was the x value at the maximum rate of development, i.e., 27℃, the value of $-b/2a$ in Eq. (4).

Thermal unit models

Fig. 2 shows the variations in the shoot length and the top fresh weight with respect to days after cutting in the four experiments with different planting dates. In all the experiments, the top fresh weight showed an exponential increase, followed by a linear growth phase. The shoot length and top fresh weight were highest in Exp. 1 and lowest in Exp. 4. The LA and LAI in time showed a sigmoid pattern in all the experiments, with the lowest final value for the single-stemmed roses cultivated in Exp. 4 (Fig. 2). The most common pattern seen under relatively stable conditions was the sigmoid pattern, in which a measurable size or weight variable sequentially went through phases that appeared to have been exponential, then linear, and finally, asymptotic to some upper limit (Pasian and Lieth, 1994). The response curve of phenological development to temperature was not linear and showed a sigmoid or a polynomial function in the leaf appearance rate of corn (Shaykewich, 1995).

The number of leaves, LA, and the fresh leaf weight showed a sigmoid curve regardless of the cutting time (data not shown). The time from bud break to harvest in Exp. 3 and 4, during which the cutting dates fell in April and June, respectively, were earlier than in the other two experiments. In this study, TUs was non-linearly related to the number of leaves, LA, and the fresh leaf weight (Fig. 3). The regression equation was $y = M\ [1 + (TUs/a)^{(b)}]^{-1}$, in which M is the maximum potential number of leaves, LA, and the fresh leaf weight. Therefore, the number of leaves, LA, and the fresh leaf weight was estimated using the TUs function. The leaf area was found to have been $578.7\ [1 + (TUs/956.1)^{-8.54}]^{-1}$ ($cm^2 \cdot ℃^{-1} \cdot d^{-1}$).

Similarly, it has been found that leaf emergencies or the unfolding of each leaf are highly correlated to the accumulated thermal units (Craufurd et al., 1998; NeSmith, 1997; Pasian and Lieth, 1994). Van den Berg (1987) reported that there is a strong positive correlation between the bud break process and temperature. When the growing period for crops is expressed as the number of days, it varies depending on the time of cutting and planting even of only one variety. If the growth period is represented in TUs, however, it can

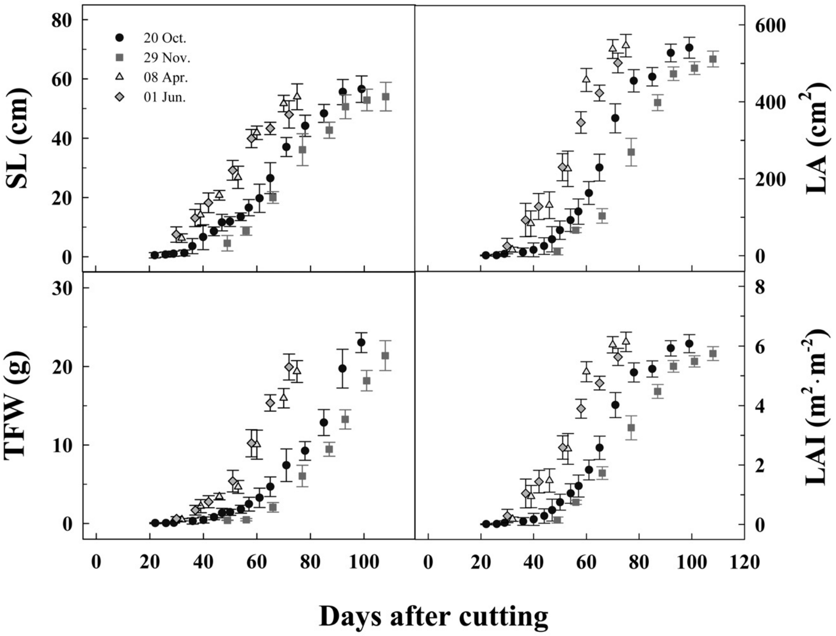

Fig. 2. Changes in shoot length (SL), top fresh weight per plant (TFW), leaf area (LA), and leaf area index (LAI) with respect to days after cutting for a single-stemmed rose 'Vital' in four experiments. Vertical bars indicate the standard errors of the mean values. Symbols indicate cutting dates of four experiments.

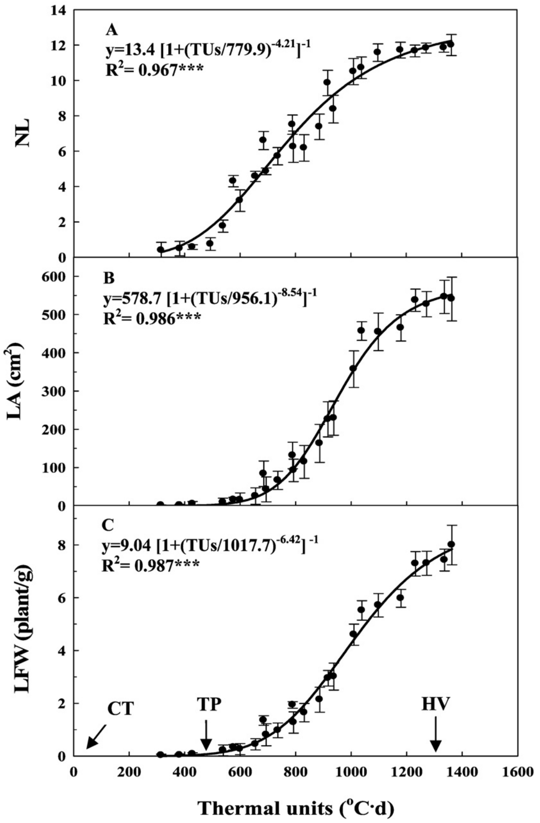

Fig. 3. Number of leaves per plant (NL), leaf area (LA), and leaf fresh weight (LFW) with respect to thermal units (TUs) after cutting for a single-stemmed rose 'Vital'. Lines represent fitted curves calculated from the TUs equation. The arrows indicate estimated cutting (CT), transplant (TP), and harvest (HV) points from a sigmoidal function, respectively. Regression equation is y=M $[1+(TUs/a)^{(b)}]^{-1}$; where, M is the maximum potential NL (A), LA (B), and LFW (C), and a and b are constants.

be shown to be a certain value regardless of whether plants develop at a low or a high temperature.

Many models have been developed for the prediction of the harvest date (the growing period). This is very relevant for production planning and marketing strategies (Marcelis et al., 1998). Thermal unit models have also been used to predict growth stages, such as leaf emergence, flowering, fruiting, and harvest. The appropriate transplant and harvest period can be estimated using the TUs function. Therefore, based on the results from our current model, we can predict that the average thermal units and standard deviation for the phases from cutting and transplant (CT-TP) and from transplant to harvest (TP-HV) were 426 ± 42℃·d and 783 ± 24℃·d, respectively.

A non-linear relationship between LA and the number of leaves (A) and between LA and the fresh leaf weight (B) was obtained (4). The leaf area could also be predicted using the exponential in Eq. (8) and the logistic functions in Eq. (9), with the variables including the number of leaves and the fresh leaf weight, besides TUs. Predicting the leaf area by the number of leaves is a non-destructive method that helps in the prediction of the growth and yield of crops.

The LA, estimated using the TUs function, the number of leaves, and the fresh leaf weight of the single-stemmed rose 'Vital', was compared with the measured LA (Fig. 5). By applying the function that describes LA as a function of TUs and the fresh leaf weight, the measured and estimated data showed a reasonably good fit at 1.116 (R^2 = 0.984***) and 1.041(R^2 = 0.989***), respectively. Many studies have

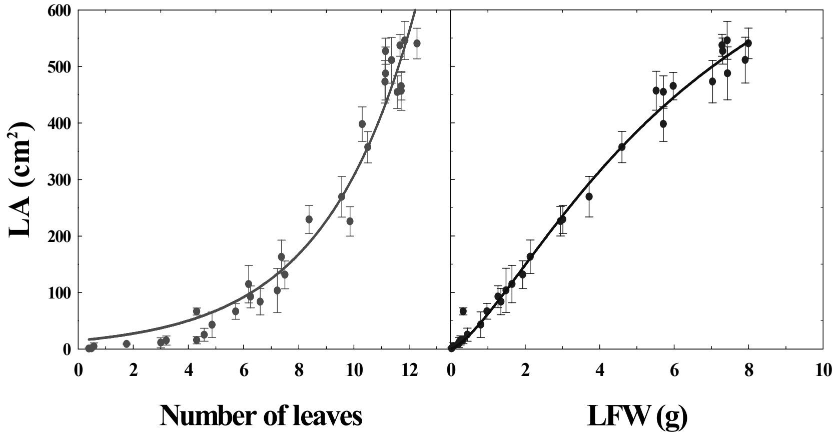

Fig. 4. Relationship between leaf area (LA) and number of leaves (NL) (A), and between LA and leaf fresh weight (LFW). Regressive equation were; LA (cm^2) = $15.06 \cdot e^{0.302 \cdot NL}$ and LA (cm^2) = $975.8/(1+(LFW/6.79)^{-1.41})$.

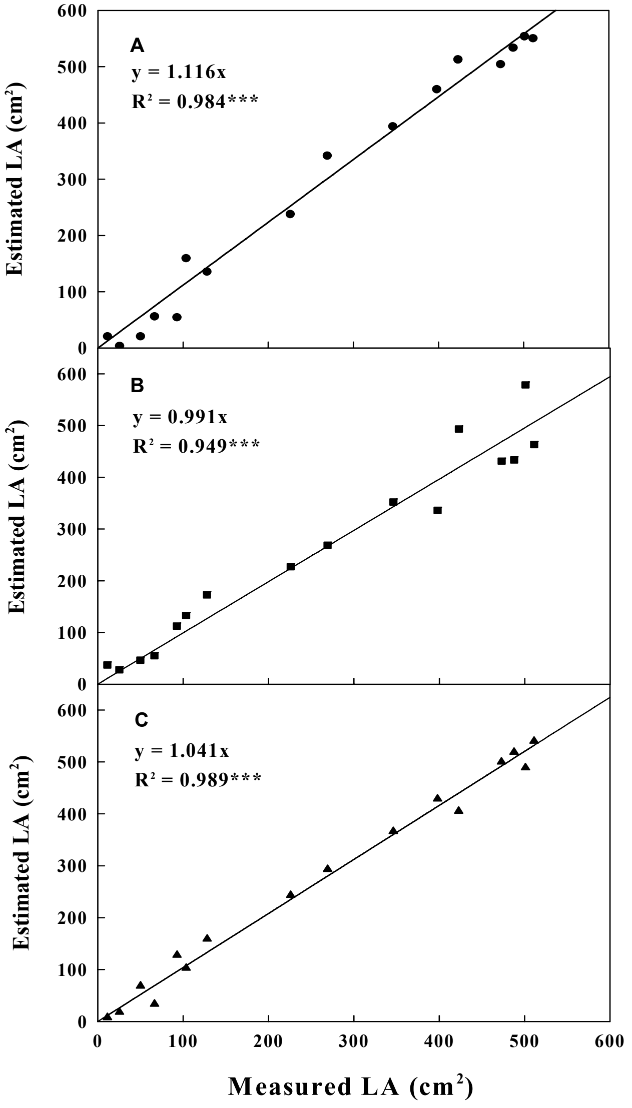

Fig. 5. Comparison of measured and estimated leaf areas of a single-stemmed rose 'Vital'. Leaf area (LA) can be estimated using the function of thermal units (A), number of leaves (B), and leaf fresh weight (C). Each dot is a mean value of 20 plants.

successfully predicted leaf area development from the number of leaves (NeSmith, 1997; Yin and Kropff, 1996). Efficient interception of the radiant energy incident to the crop surface requires an adequate leaf area that is uniformly distributed to give complete ground cover (Gardner et al., 1985; Langton, et al., 1999). Leaf area development can be simulated accurately on the basis of the plant's developmental stage (temperature sum) in situations when radiation is rather constant or strongly correlated with temperature (Goudriaan and Monteith, 1990).

A more flexible way of simulating the leaf area is by calculating it based on the simulated leaf biomass and SLA. This approach has been used for several crop models (Gijzen et al., 1998; Heuvelink, 1996; Lieth and Pasian, 1991; van Henten, 1994). For rose plants, leaf area development has been simulated as a function of the estimated leaf weight multiplied by the specific leaf area (Lieth and Pasian, 1991).

Fig. 6 shows a comparison of the estimated and observed shoot lengths and the fresh leaf weight in Exp. 2 and Exp. 4. They showed a reasonably good fit at 1.060 (R^2 = 0.976***) and 1.043 (R^2 = 0.955***), respectively. Some overestimation of the shoot length and the fresh leaf weight was observed in Exp. 4, at the later period of the cultivation (Fig. 6). This overestimation in the hot season was probably the result of decreased biomass production from high humidity with increasing irradiance and temperature in the plant factory, which used natural and artificial lighting systems.

According to the results of the study, it was concluded that shoot development and leaf area development could be estimated using the TUs function. A thermal unit is also useful in developing a crop growth model as a function of temperature for single-stemmed roses in a plant factory system. Therefore, it is expected that the present data can be used to accurately simulate observed growth patterns under a wide range of glasshouse climatic conditions and

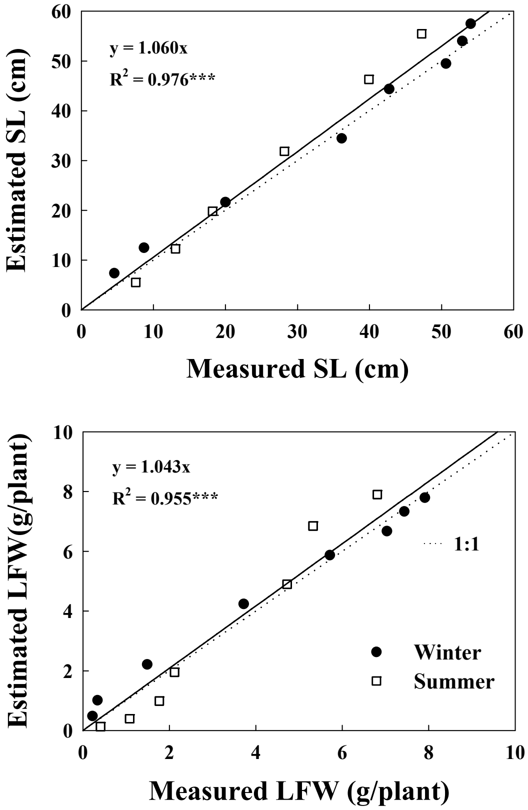

Fig. 6. Comparison of measured and estimated shoot length (SL) and leaf fresh weight (LFW) of a single-stemmed rose 'Vital'. The SL and LFW can be estimated using the sigmoidal function of thermal units. Each dot is a mean value of 20 plants.

may serve as references in the formulation of production planning and marketing strategies for cut-flower roses.

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식물공장 시스템에서 Thermal Units을 이용한 Single-Stemmed Rose 'Vital'의 신초발달 예측

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초　록. 본 실험은 thermal units을 이용하여 single-stemmed rose(*Rosa hybrida* L.) 'Vital'의 초장, 생체중 및 총엽면적과 각 생육단계에 도달하는 시간을 예측하고, 장미의 신초발달 모델을 개발하기 위해 수행하였다. 기저온도(T_b), 적정온도(T_{opt}), 및 최대온도(T_{max})는 신초의 발달율과 평균온도의 회귀를 통해 예측하였다. 삽목에서 정식(CT-TP)까지의 생육단계에 대한 신초의 발달율은 linear 함수인 $R_b(d^{-1}) = -0.0089 + 0.0016 \cdot \text{Temp}$으로 나타났다. 정식에서 수확(TP-HV)까지의 생육단계에서 신초의 발달율은 parabolic 함수인 $R_h(d^{-1}) = -0.0001 \cdot \text{Temp}^2 + 0.0054 \cdot \text{Temp} - 0.0484$으로 나타낼 수 있었다. T_b, T_{opt} 및 T_{max}는 각각 5.56, 27.0, 및 42.7℃으로 나타났다. T_b값 5.56℃은 single-stemmed rose의 신초발달에 대한 온도함수인 thermal units 계산에 이용되었다. 엽수, 엽면적 및 엽중은 삽목시기에 상관없이 sigmoid curve를 나타내었다. 엽면적(LA) 모델은 thermal units를 사용하여 sigmoid 함수, $\text{LA} = 578.7\ [1 + (\text{thermal units}/956.1)^{-8.54}]^{-1}$로 기술할 수 있었다. 삽목에서 정식(CT-TP)과 정식에서 수확(TP-HV)까지의 생육단계에 있어서 요구되는 평균 thermal units(℃·d)는 각각 426 ± 42(℃·d)과 783 ± 24(℃·d)였다.

추가 주요어 : 기저온도, 생육모델, 엽면적, 단경삽목, sigmoid 함수