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https://doi.org/10.5109/23670

出版情報：九州大学大学院農学研究院紀要. 22 (4), pp.233-241, 1978-07. Kyushu University

J. Fac. Agr., Kyushu Univ., 22. 233-241 (1978)

Mathematical Model of Flower Stalk Development in Chinese Cabbage in Response to Low Temperature

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(Received April 19, 1978)

A model of the flower stalk development in Chinese cabbage in response to low temperature was presented for the use in environment control of plant growth and development. The pattern of flower stalk development in response to low temperatures appeared in the sigmoid curve in time course and was fitted to the logistic curve. The asymptote of the logistic curve was given by the functions of treating duration (t_d) and degree (ΔT) of the subtraction of treating temperature from 20°C (untreating condition). In order to evaluate the *delay* in rise of flower stalk development, the logistic curve was appoximated to the first order lag curve having the same asymptote and the same differential coefficient at 63.2 % of the asymptote as those of the logistic curve. From the equation of the first order lag curve, the time constant (T) and the dead time (L) were calculated to obtain the time of *delay* by summing T and L. The correlation coefficient of the time of *delay* on $\log_{10}\Delta T^{1/2}\cdot t_d^2$ was the largest and significant at 0.1 % level. From this finding, it is clear that log,, $\Delta T^{1/2}\cdot t_d^2$ is usable for evaluating the efficiency of low temperature on flower stalk development. Thus, the model of flower stalk development was represented by a function of treating temperature, treating duration and time after low temerature treatment.

INTRODUCTION

For making adequate programs of environment control of plant growth and development, it is needed to evaluate the plant response to environmental factors quantitatively (Matsui *et al.,* 1977). As one of the important factors, temperature is well known to be responsible for vegetative and reproductive growth. In paticular, the low temperature or temperature dropping affects various morphogeneses such as flower induction, bolting and the other differentiations in plants. In many kinds of *Brassica* species, low temperature promotes the change of the rosette type of the seedling into the bolting type under long-day condition (Eguchi and Koide, 1944; Kagawa, 1966; Lorenz, 1946; Yamasaki, 1956). In this study, it was attempted to establish the model of the flower stalk development in Chinese cabbage in response to low temperature.

MATERIAL AND METHODS

Plant material

Chineses cabbage, *Brassica pekinensis* Rupr. "Nagaoka-kohai Taibyo-rokujunichi", was used in this experiment. Flower differentiation and flower stalk development (bolting) in this variety are known to be promoted by low temperature under suitable photoperiodic conditions.

Treatment

Seeds were germinated, and plants were grown under controlled environment at air temperature of 20±2°C, relative humidity of 75±10% and photoperiod of 8 hours with the light intensity of about 300 μE m^{-2} sec^{-1} (metal halide lamps). Fifteen days old plants were treated with respective temperatures of 2, 5, 8 and 11 ±1°C for respective durations of 5, 10, 15 and 20 days under artificial light (18 white fluorescent lamps of 40 W and 6 tungsten lamps of 200 W) with the light intensity of about 200 μE m^{-2} sec^{-1} and the photoperiod of 8 hours, using 10 plants per experimental plot. After the treatments, plants were cultivated under air temperature of 20±2°C, relative humidity of 75±10% and continuous lighting (metal halide lamps) with the intensity of about 300 μE m^{-2} sec^{-1}. Untreated plants were grown under continuous lighting from 16 to 66 days after germination at a constant temperature of 20±2°C. The distance between cotyledonary node and shoot apex was measured every day to evaluate flower stalk development.

RESULTS AND DISCUSSION

Examination of flower stalk development

Figure 1 shows patterns of flower stalk development in time course after treatments with respective temperatures for different durations. Flower bud formation was found in all plants in respective treatments. Appreciable dif-

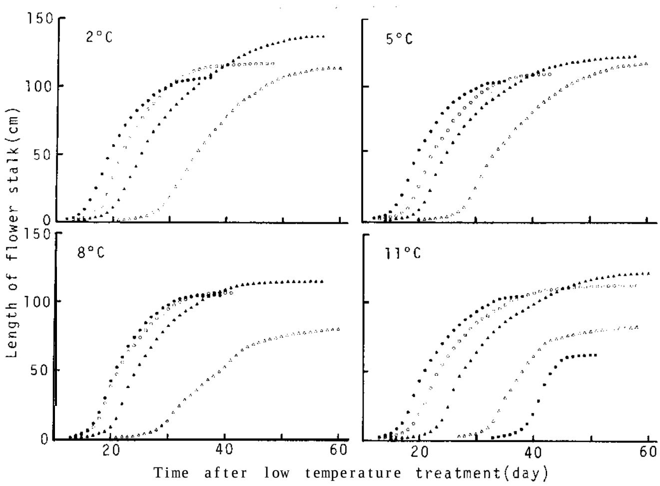


Fig. 1. Patterns of flower stalk development in respective treatments with low temperatures. △; treating duration of 5 days, ▲; 10 days, ○; 15 days, ●; 20 days, ■ ; untreated.

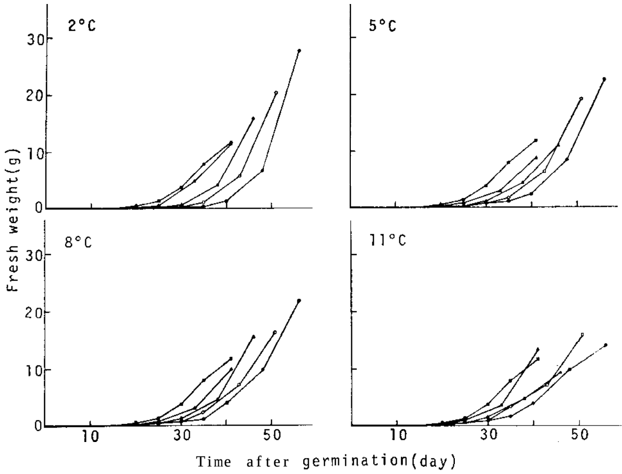


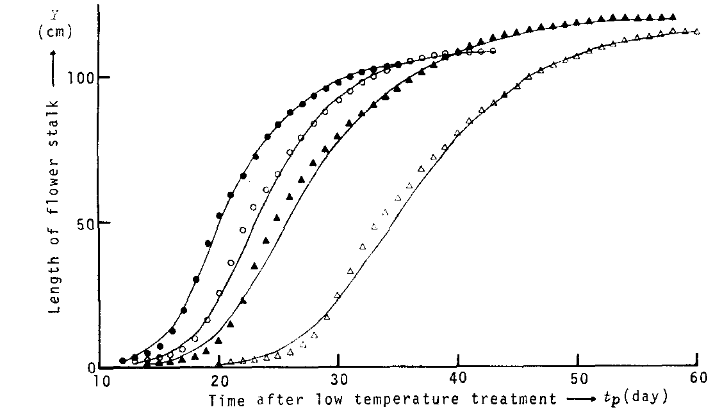
Fig. 2. Patterns of fresh weight (vegetative growth) in respective treatments with low temeratures. △; treating duration of 5 days, ▲; 10 days, ○; 15 days, ●; 20 days, ■ ; untreated.

ferences among plants treated with respective temperatures were observed in final length of flower stalk and also in *delay* in rise of flower stalk development: The final length of flower stalk was the largest in the treating duration for 10 days under respective treating temperatures, and lower treating temperatures and longer treating durations shortened the *delay* in rise of flower stalk development. While, increase of fresh weight (vegetative growth) delayed under longer treating durations with respective low temperatures, as shown in Fig. 2. Thus, low temperature treatment resulted in promotion of the flower stalk development and in inhibition of the vegetative growth. In this experiment, the flower stalk development was used as an example of plant responses to low temperature for evaluating the efficiency of the temperature.

Mathematical representation

The pattern of the flower stalk development appeared in the sigmoid curve in time course and was fitted to the logistic curve (Richards, 1969) given by the function of time (t_p, day) after low temperature treatment. Figure 3 shows the measured values of flower stalk and the fitted logistic curves in treatments with 5°C for respective treating durations. Figure 4 shows measured asymptotes of the logistic curves in respective treatments. The asymptote was affected clearly by treating duration; the asymptote was the largest in the treatments for the treating duration of 10 days, and the dependency of the asymptote on the treating duration appeared in similar patterns in respective treatments with different temperatures. From this appearance, the asymptote (Ks, cm) was fitted to the function of common logarithm of the treating duration (t_d, day), and the regression equation was given by

$$Ks = a_0 + a_1 \log_{10}(t_d + \varepsilon) + a_2\{\log_{10}(t_d + \varepsilon)\}^2 \qquad (1)$$



Fig, 3. Measured values of flower stalk and the fitted logistic curves in respective treating durations at 5°C. ▲; treating duration of 5 days. △; 10 days, ○; 15 days, ●; 20 days, ——; logistic curve defined as $Y=K[1+\exp\{f(t_p)\}]^{-1}$, $f(t_p)=b_0+b_1t_p+b_2t_p^2+b_3t_p^3$.

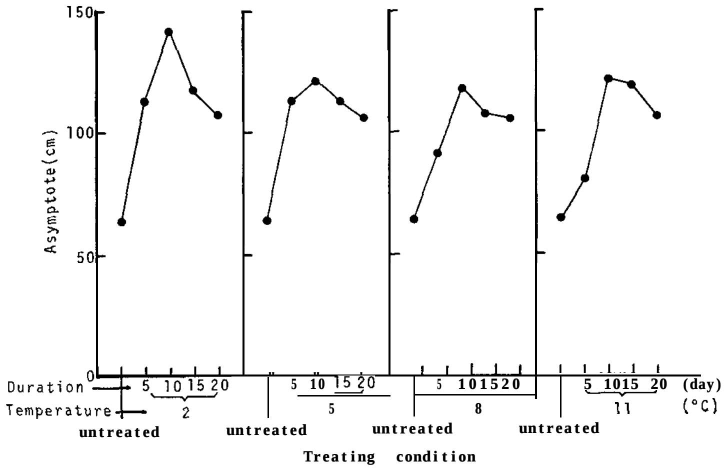


Fig. 4. Asymptotes of the fitted logistic curves in respective treatments.

where ε is treated as 5 (days) in this case to make $t_d+\varepsilon>0$, and a_0, a_1 and a_2 are given by the functions of degree (ΔT, °C) of the subtraction of treating temperature from 20°C (untreating condition), that is,

$$\left.\begin{aligned} a_0 &= 207-28.4\Delta T \\ a_1 &= -372+62.5\Delta T \\ a_2 &= 218-30.6\Delta T \end{aligned}\right\} \qquad (2)$$

From Eqs. (1) and (2), Ks was given by the function of ΔT and t_d,

$$Ks=(207-28.4\Delta T)-(372-62.5\Delta T)\log_{10}(t_d+5) \\ +(218-30.6\Delta T)\{\log_{10}(t_d+5)\}^2 \qquad (3)$$

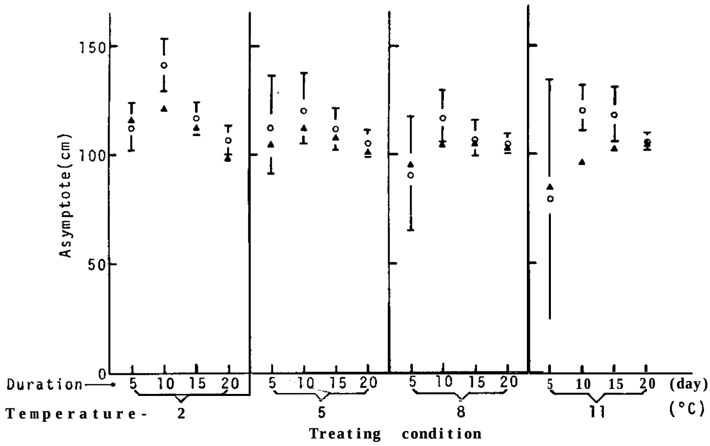


Fig. *5.* Asymptotes of the fitted logistic curves, 95% confidence intervals **and** asymptotes (Ks) calculated from Eq. (3) in respective treatments. ○; asymptote of the fitted logistic *curve.* ▲; asymptote (*Ks*) calculated from Eq. (3).

Figure 5 shows measured asymptote, 95% confidence interval and the asymptote (Ks) calculated from Eq. (3) in respective temperature treatments. Most of the *Ks*'s existed within the 95 % confidence intervals. From this fact, it was estimated that the asymptote corresponding to a final length of flower stalk could be represented by the function of treating temperature and treating duration.

As mentioned before, one of the characteristics of low temperature effect was observed in *delay* in rise of flower stalk development. So, in order to evaluate the *delay,* the logistic curve of flower stalk development was approximated to the first order lag curve having the same asymptote and the same differential coefficient at 63.2 % of the asymptote as those of the logistic curve, as shown in Fig. 6. From this equation of the first order lag curve, the time constant (*T*) and the dead time (*L*) were calculated to obtain the time of

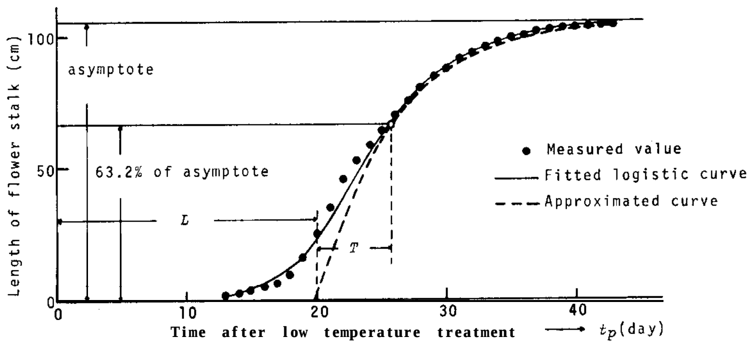


Fig. 6. Measured values of flower stalk. fitted logistic curve and approximated **curve of first order lag.** *T;* **time constant,** *L;* **dead time.**

'Table 1. Correlation coefficients of time of *delay* on various combinations of parameters (ΔT and t_d).

Treating parameter combinations of AT and t_d	Correlation coefficients of time of delay
$\log_{10}\Delta T\cdot t_d$	0.889***
$\log_{10}\Delta T\cdot t_d^{2}$	0.946***
$\log_{10}\Delta T^{2}\cdot t_d$	0.730**
$\log_{10}\Delta T^{2}\cdot t_d^{1/2}$	0.496*
$\log_{10}\Delta T^{1/2}\cdot t_d^{2}$	0.958***
$\log_{10}\Delta T\cdot t_d^{-1}$	0.823***
$\log_{10}\Delta T\cdot t_d^{-2}$	0.910***
$\log_{10}\Delta T^{2}\cdot t_d^{-1}$	0.625**
$\log_{10}\Delta T^{2}\cdot t_d^{-1/2}$	0.363
$\log_{10}\Delta T^{1/2}\cdot t_d^{-2}$	0.939***

* Significant at 5% level, ** Significant at 1% level,
*** Significant at 0.1% level

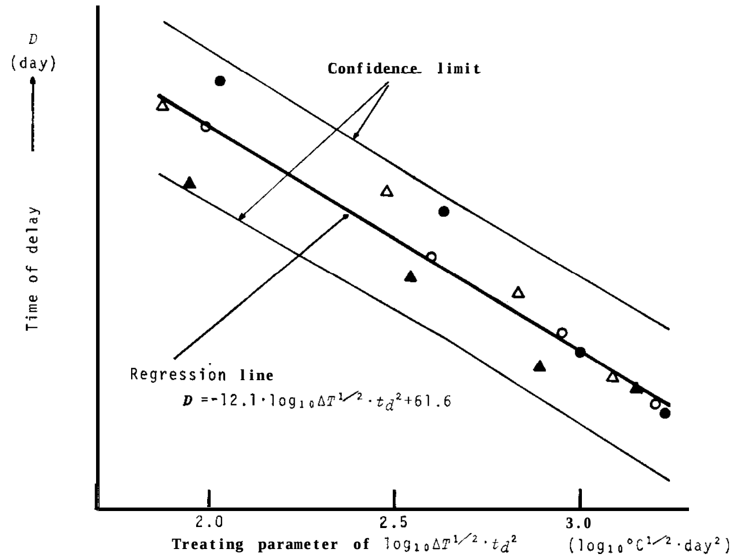


Fig. 7. Distributions of time of *delay* in rise of flower stalk development on the parameter, log,, $\Delta T^{1/2}\cdot t_d^{2}$, in all treatments. ● ; 2°C, ○; 5°C, △; 8°C. A; 11°C.

delay by summing T and L. On the other hand, the accumulated temperature in terms of *degree hours* is used in general, for evaluating the plant response to temperature (Aron, 1975; Yamasaki, 1956). So, the various combinations of AT and t_d were set for selecting a parameter enough to evaluate the efficiency of low temperature. Correlations between the time of *delay* and various combinations of the parameters (AT and t_d) were examined. Table 1 shows correlation coefficients of the time of *delay on* various combinations of ΔT and t_d. The correlation coefficient of the time of *delay* on common logarithm of $\Delta T^{1/2} \cdot t_d^2$ was the largest and significant at 0.1% level. From this result of the statistical analysis, it was the suggested that $\log_{10} \Delta T^{1/2} \cdot t_d^2$ could be an important parameter to evaluate the efficiency of low temperature on the *delay* in rise of flower stalk development. Figure 7 shows distributions of time of *delay* in rise of flower stalk development in all treatments on the parameter, $\log_{10} \Delta T^{1/2} \cdot t_d^2$. In these distributions, regression equation of the time (D) of *delay* was represented by the function of $\log_{10} \Delta T^{1/2} \cdot t_d^2$,

$$D = 61.6 - 12.1 \log_{10} \Delta T^{1/2} \cdot t_d^2 \tag{4}$$

Furthermore, the dead time (L) is also represented by

$$L = 73.2 - 28.7 \log_{10} \Delta T^{1/2} \cdot t_d^2 + 3.50 (\log_{10} \Delta T^{1/2} \cdot t_d^2)^2 \tag{5}$$

Figure 8 shows the time of *delay* measured and the D calculated from Eq. (4), and also 95% confidence intervals of the time of *delay* measured in respective temperature treatments. Each of the calculated D's was nearly equal to the time of *delay* measured, and most of them existed within 95 % confidence intervals. Thus, it is concluded that $\log_{10} \Delta T^{1/2} \cdot t_d^2$ is enough to be used for evaluating the efficiency of low temperature affecting the *delay* in rise of flower stalk development.

As mentioned before, the logistic curves of flower stalk development was approximated to the first order lag curve. This equation of the first order lag curve was reduced to the equation which satisfies Eqs. (3), (4) and (5)

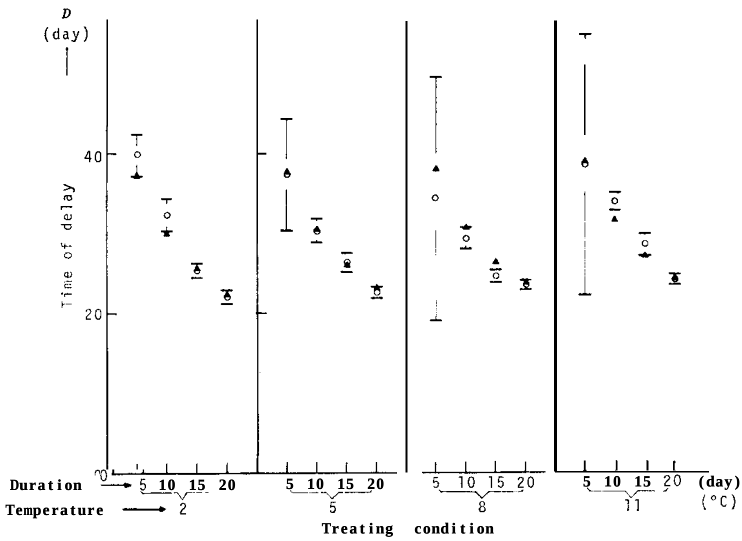


Fig. 8. Measured and calculated times of *delay* in respective treatments. ○; measured time of delay, ▲; calculated time (D) *of delay*.

and used as a model of flower stalk development affected by low temperature. The equation is expressed as

$$Ys = Ks[1\text{-}\exp\{g(t_p)\}] \tag{6}$$

where Ys is length of flower stalk, $g(t_p)=L/T-t_p/T$ (Richards, 1969).

So, the model of flower stalk development is given by

$$Ys=\{(207-28.4\Delta T)-(372-62.5\Delta T)X_1+(218-30.6\Delta T)X_1^2\}$$
$$\times[1\text{-}\exp\{(73.2-28.7X_2+3.50X_2^2-t_p)/(-11.6+16.6X_2-3.50X_2^2)\}] \tag{7}$$

where $X_1=\log_{10}(t_d+5)$, $X_2=\log_{10}\Delta T^{1/2}\cdot t_d^2$, $5\leq t_d\leq 20$, $9\leq\Delta T\leq 18$, $0<t_p\leq 60$.

It is obvious from Eq. (7) that flower stalk development in response to low temperature can be represented by the function of treating temperature, treating duration and time after low temperature treatment. Figure 9 shows examples of the simulation of flower stalk development, based on the present model. Simulated and measured patterns closed to each other, and this mathematical model was estimated to be adequate for evaluating the flower stalk development in response to low temperature. This fact demonstrates that $\log_{10}\Delta T^{1/2}\cdot t_d^2$ is usable as treating parameter for quantitative evaluation of plant response to the low temperature.

Present experiment was carried out under continuous lighting in post-culture, in order to examine clearly the promotive effect of low temperature on flower stalk development. It could be considered that the lighting condition might be responsible for the temperature effect on flower stalk development.

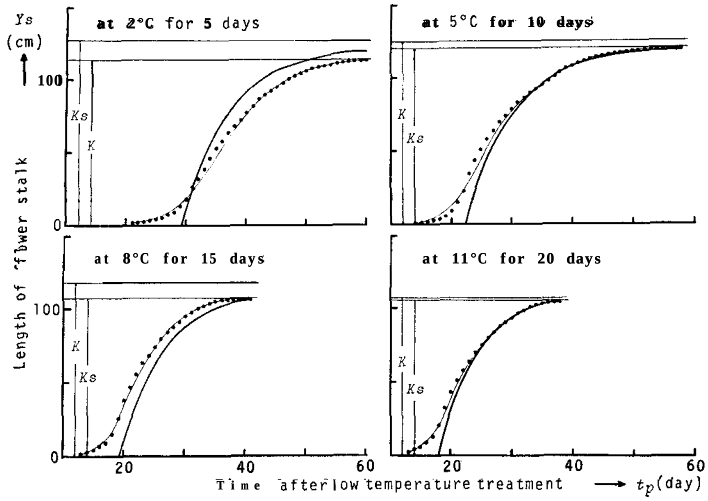


Fig. 9. Measured values of flower stalk, fitted logistic curves and curves of model in some treatments. •; measured value, ——; fitted logistic curve, ▬▬; curve (Ys) of model.

This consideration will be taken into next studies, and the present model could be further developed and modified with lighting parameters.

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