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A New Method for Predicting Flowering Stage in Soybean

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Abstract
A new method, called a DVR-DVI method, has recently been developed for predicting flowering stage of soybean plants, which has proved to be more practical and accurate than the traditional thermal unit method in many cases. Under the DVR-DVI method, emergence and flowering stage are represented by numerical values of 0 and 1.0, respectively. Such values are termed DVI, through which a model of the growth of soybean plants is constructed. Increment of DVI on each day is defined as DVR, which is calculated by a model, taking into account weather factors of each day. Such a model is the basis for predicting flowering date and indicating varietal differences of the related characteristics. Models for several varieties of soybean, which reflected their respective DVR for daily mean air-temperature and daylength, were developed on the basis of results of a field experiment with some daylength treatments. These models clearly explain complex responses of soybean to weather factors and varietal differences in earliness. They also show that dependence of DVR on temperature changes in accordance with daylength.

Discipline: Agro-meteorology
Additional key words: developmental index (DVI), developmental rate (DVR), model, phenology

Introduction

Soybean plants are highly sensitive to weather conditions, showing quite diverse patterns of development in accordance with their changes. It is a useful information for cropping plan and management to predict how soybean plants develop under a certain weather condition. A great number of studies have been conducted in special regard to crop-weather relationships in soybean phenology. Many of those studies have placed great emphasis on flowering stage, the information from which are easy to notice and practically important.

Some effective methods have been proposed to quantify to what extent weather conditions hasten or put off soybean flowering stage. Thermal unit or accumulated effective temperature is probably the most simple and commonly-used method. It is very easy to use. Its applicability however is considerably limited, because it is calculated from air temperature alone, assuming a linear relationship between the developmental rate and temperature. Some revised versions were proposed to avoid the causal disadvantages[3].

In recent years, a more sophisticated method has been developed and proved to have wider applicability with higher precision than the traditional method. It is called a DVR–DVI method. The purpose of this paper is to outline the concept of the DVR–DVI method and propose newly developed models to calculate DVR for several varieties.

Basic concept of the DVR–DVI method

1) From thermal unit to DVR–DVI method

Thermal unit from seeding to flowering (TUf, expressed in unit of degree days) is calculated as follows:

$$\mathrm{TUf} = \sum_{i=1}^{n} (Ti - \mathrm{Tb}), \quad \text{.........................} \quad (1)$$

where, Ti is daily mean air-temperature on the i'th day (emergence occurs on the first day and flowering on the n'th day); and Tb is outward base air-temperature, below which soybean plants do not develop. The balance of Ti–Tb is called effective temperature.

The flowering day can be predicted by accumulating the daily effective temperatures after the emergence day, assuming that flowering takes place when the sum reaches TUf. Tb and TUf are emprically obtained in general. Those values of zero and TUf represent thermal units at the emergence and flowering stages, respectively. Soybean plants get nearer to their flowering stage by the degree of (Ti–Tb) over TUf on the i'th day. In other words, the rate of development for that particular day is (Ti–Tb)/TUf, which is hereunder called DVRi (DVR is the abbreviation of developmental rate, and a subscript indicates concerned date).

$$DVRi = (Ti - Tb)/TUf \quad \ldots\ldots (2)$$

Then, dividing both sides of the equation (1) by TUf gives:

$$1.0 = \sum_{i=1}^{n} DVRi \quad \ldots\ldots (3)$$

A new concept of developmental index (DVI), which is the sum of DVR, is hereto introduced. Based on this term, the equation (3) means that DVI is 1.0 at the flowering stage, and as a matter of course, DVI is zero at the emergence stage. DVI on the j'th day (DVIj) indicates to what extent a soybean plant has relatively developed at that time. DVIj is calculated through the following equation:

$$DVIj = \sum_{i=1}^{j} DVRi \quad \ldots\ldots (4)$$

DVIj is regarded as relative phenological age of a soybean plant. Thus, the growth stages of soybean plants are numerically presented by DVI. DVR, i.e. an increment of DVI per day, is calculated by a model, taking into account weather factors of each day. In applying this model, it is assumed that no change takes place in the relationship of DVR with daily weather factors throughout the period from emergence to flowering. This model provides a basis for predicting a flowering date of the soybean plant under study. The daily DVR is summed, starting on emergence day. It is predicted that flowering takes place on the day when the DVI becomes larger than 1.0.

This DVR–DVI concept was originally proposed by de Wit[1] and the terminologies adopted here follow Horie et al.[4]. One of the advantages of employing the DVR–DVI method is that DVR can be obtained on the basis of arbitrary factors with arbitrary functions. The above equation (2) is an instance of DVR model, which is the simplest but may possibly lead to greater errors. More accurate estimates are therefore needed.

2) Modeling DVR

In case where only temperatures (T) are taken into consideration as an external condition, DVR is expressed as follows:

$$DVR = f(T) \quad \ldots\ldots (5)$$

Logistic function is often used for $f(T)$. That is:

$$DVR = a/\{1 + \exp(b - c \cdot T)\}, \quad \ldots\ldots (6)$$

where a, b and c are parameters. Their values are obtained, for instance, by comparing calculated and actually observed flowering dates as follows. The flowering dates can be calculated from the model with arbitrary parameter values. The predicted dates, however, may differ from the observed flowering dates. Then, a, b and c are modified to minimize the deviation between the predicted and observed flowering dates. This onerous procedure could be completed rather easily with a computer[7]. Some other functions than the logistic one are proposed[10].

It is well known that soybean plants greatly change their flowering dates in response to varied day-length[2]. In many cases, DVR has to be constructed so that the functions of both temperature and day-length (DL) could be adequately reflected. It is expressed as follows:

$$DVR = f(T) \cdot g(DL)$$

or $\quad \ldots\ldots (7)$

$$DVR = f(T) + g(DL).$$

Many functions have been proposed for estimating $f(T)$ and $g(DL)$. Kawakata[6] discussed some functions in paddy rice. Parameters are obtained in the same way as mentioned above.

New models

In formulating the equation (7), it is assumed that the relationship of DVR with temperature is entirely independent from daylength. It is observed however that DVR occasionally increases steadily with temperature under short daylength, while it reaches a plateau under long daylength. On the basis of investigated phenomenon on several soybean varieties, new models are herewith proposed, in which the relationship of DVR with temperature changes with varying daylength.

1) Materials and method

(1) Field experiment

In 1985, soybean plants were seeded on 6 dates at a two-week interval during the period of May 10 to July 19 at the National Agriculture Research Center, Tsukuba, Ibaraki, Japan. Three daylength treatments were given to keep experimental plots under constant daylength of 13.3, 14.3, 15.3 hr a day throughout the growing season by putting light sealed boxes on/off every day. Since these boxes had openings for ventilation, there were negligible temperature and humidity differences between inside and outside these boxes. Daily mean air-temperature and flowering dates for each plot were recorded. Six varieties of soybean, including Kitahomare, Suzuyutaka, Raiden, Enrei, Tamahomare, Akiyoshi, were selected for the experiment. The daylength adopted here is defined as the period during the sun elevation is above −3°C, which was calculated from the forms available[5].

(2) Modeling DVR

Because the daylength was kept constant at the above-noted three levels each, the following relationships were obtained for the respective daylength in the same way as the case for the equation (5).

$$\begin{aligned} \mathrm{DVR}_{\mathrm{DL}_1} &= \mathrm{f}_1(T) \\ \mathrm{DVR}_{\mathrm{DL}_2} &= \mathrm{f}_2(T) \qquad (8) \\ \mathrm{DVR}_{\mathrm{DL}_3} &= \mathrm{f}_3(T)\,, \end{aligned}$$

where, $\mathrm{DVR}_{\mathrm{DL}_n}$ is DVR under DL_n. DL_1, DL_2 and DL_3 are daylengths of 13.3, 14.3, 15.3 hr, respectively. Thus, DVR at each daylength level is quantified independently. Through proportional allocation by daylength, DVR for any DL is calculated as follows:

$$\mathrm{DVR} = \mathrm{f}_1(T) + \frac{(DL-\mathrm{DL}_1)\cdot(\mathrm{f}_2(T)-\mathrm{f}_1(T))}{(\mathrm{DL}_2-\mathrm{DL}_1)} \quad (\mathrm{DL}_1 \le DL < \mathrm{DL}_2)$$

or

$$\mathrm{DVR} = \mathrm{f}_2(T) + \frac{(DL-\mathrm{DL}_2)\cdot(\mathrm{f}_3(T)-\mathrm{f}_2(T))}{(\mathrm{DL}_3-\mathrm{DL}_2)} \quad (\mathrm{DL}_2 \le DL \le \mathrm{DL}_3). \qquad (9)$$

2) Results and discussion

Interrelated patterns of DVR under varying temperatures and daylengths are shown in Fig. 1 for the following three varieties: Kitahomare, Tamahomare and Akiyoshi. These patterns are obtained from the model equations, which are revisions of the Sameshima and Iwakiri's[8]. In all cases, DVI is zero at the seeding date. Two figures for each variety show different aspects of the same model: the left-hand figure shows patterns in three dimensions and the right-hand one shows them with contour lines of DVR.

Soybean plants respond to temperature and daylength in a complex manner. Their responses can however be understood rather easily through those models illustrated in Fig. 1. It has been recognized that a varietal difference in the duration needed before flowering is small under short daylength, while that is large under long daylength[9]. Fig. 1 can clearly explain this phenomenon. The DVR for each variety does not significantly differ under short daylength over the temperature range under testing, and there are great differences among the varieties tested under long daylength (refer to left-hand figures). Such varietal differences seem to be mainly attributed to the daylength sensitivity. Kitahomare has low sensitivity to daylength, which is presented by its DVR contour lines nearly parallel to daylength axis, while Akiyoshi has high sensitivity to daylength (see right-hand figures). Taking this difference into account, Kitahomare is called "early variety", the growing season of which is relatively short by maintaining relatively high DVR values throughout the daylength range. On the other hand, Akiyoshi is called "late variety", whose growing period is generally long due to its higher sensitivity with lowered DVR. Tamahomare is intermediate between these two varieties.

Fig. 1 shows that the temperature-dependent patterns of DVR are also affected by daylength. In the case of Akiyoshi, DVR reaches a plateau under a short day condition, which is not the case with long daylength. This phenomenon is not observed in

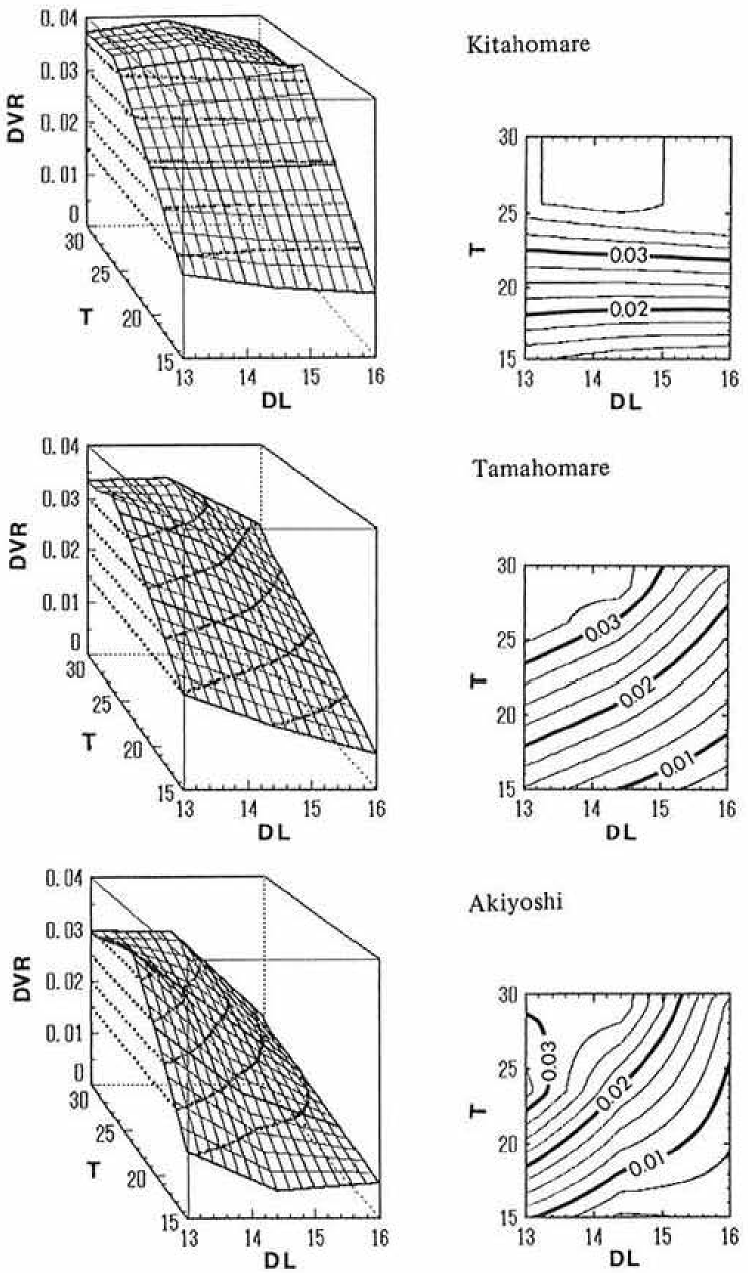

Fig. 1. DVR models for three soybean varieties
DVR: Developmental rate per day,
DL: Daylength (hr),
T: Mean air-temperature (°C).

Kitahomare having low sensitivity to daylength.

Conclusion

Relative phenological ages of soybean plants could be estimated with the above-proposed model based on DVI, which is an integral of DVR. The DVR is obtained as a function of weather factors.

The new models as proposed above to calculate DVR for soybean varieties could be made available not only to predict flowering date but also to analyze varietal difference of soybean earliness. In addition, the DVR models could be applicable for physiological analyses, though their physiological significance has to be adequately justified.

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