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CLIMATIC CONTROL OF *ARABIDOPSIS THALIANA* (L.) HEYNH. DEVELOPMENT

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A b s t r a c t. In pot and field experiments the emergence, budding, flowering and ripening of *Arabidopsis thaliana* were observed. The quantitative relationships between phenology and climatic factors were determined using mainly multiple regression methods. Duration of periods between sowing and emergence and between flowering and ripening may be treated as hyperbolic functions of mean temperature and therefore the usual degree-day method can be applied. In the period between emergence and flowering the relationships are more complex; some modifications of methods relating development to temperature were used. A short vernalization after emergence, thereafter higher temperatures at long days accelerate flowering.

K e y w o r d s: *Arabidopsis thaliana*, degree-day method, phenology, photoperiod, vernalization

INTRODUCTION

Arabidopsis thaliana L. has been frequently used as an experimental plant by plant physiologists and geneticians [13] because of its very short life cycle (about 6 weeks from seed to seed). Many reports have been published also concerning the role of climatic conditions in the regulation of its development, particularly temperature, photoperiod and spectral composition of light [1,3,11,14]. These studies were conducted almost exclusively under artificial conditions, where all climatic elements (except those under consideration) were fixed. The aim of the present study was to describe the quantitative relationships between the development of *Arabidopsis* and the climatic environment under natural (field) or semi-natural (pots) conditions, where all the climatic factors undergo natural variability.

METHODS

Plants used in our experiments were grown from seeds collected near Puławy in 1986. Three phenological phases were observed in each experiment: emergence - when the cotyledon was visible, budding - when flower buds could be seen by naked eye, flowering - when white petals appeared. During one year also ripening - when most of siliquas dried and turned yellow.

During the years 1987-1991 several series of experiments of two kinds were conducted. The seeds were sown in plastic pots or in the field on the soil surface without covering, since they are extremely positively photoblastic [8]. The pots of 12 cm diameter were filled with 900 g of fertile loamy sand soil. No fertilizers were applied. About 10 seeds were sown per pot; after emergence plants were thinned to one per pot. The sowings were at about one week intervals between March and September; a certain proportion of the pots were located in the open, the others in an unheated glasshouse, where the temperature was several degrees higher. Every sowing in the field consisted of one row 1.5 m long and 30 cm apart from other sowings. On the whole plants in 96 pots and 37 rows in the field were observed.

Plants in pots were regularly watered; no watering was applied in the field experiments. In all pot experiments temperature was recorded using resistance thermometers in small wooden screens located within the pots. Temperature data for field experiments came from a nearby Puławy meteorological station.

The main statistic tool for interpretation of the experimental results was multiple regression analysis. We used the concept of 'rate of development' (i.e., reciprocity of period length); its usual advantage is the linearity of the effects of temperature [9,12]. For the quantification of these effects the degree-days (temperature summation) method was also used. The choice of base (threshold) temperatures was calculated using the equation [6]:

$$a = \frac{\bar{T}\,\overline{LT} - \overline{LT^2}}{\bar{L}\,\bar{T} - \overline{LT}} \qquad (1)$$

where a - base temperature (°C), T - mean temperature of the period, L - length of the period in days. A dash above a value means that the value is averaged over the whole sample of data.

RESULTS AND DISCUSSION

The duration of interphase periods was studied as a function of temperature (sowing - emergence and flowering - ripening periods) or a multiple function of temperatures (chilling and current) and photoperiod (emergence - flowering period). Since the error of bud appearance evaluation seems to be relatively high and the subperiod budding - flowering lasts normally only several days, we have combined the whole period emergence - flowering.

It was proved (as formerly [5,7]) that there were no differences in phenological responses to climatic factors between pot and field experiments, and therefore all the data could be joined. However, taking into consideration that germination may depend also on the availability of soil water, we used only the field experiments with natural watering to describe the sowing - emergence period.

Period sowing - emergence

Using 37 observations from field experiments, the following hyperbolic equation (typical for the dependence of period length on temperature) was obtained:

$$L = \frac{88}{T - 1} \qquad (2)$$

with the coefficient of determination $R^2 = 0.75$ and the standard error S.E. = 1.9 days.

It follows that the temperature sum is 88 above the base 1 °C and that the linear equation is:

$$C = -\,0.0114 + 0.0114\,T \qquad (3)$$

where C - rate of development (reciprocity of period length in days).

Using Eq. (2) emergence in relation to mean temperature can be easily calculated. At temperature 10 °C it lasts normally about 10 days (88/9), at temperature 23 °C - 4 days. Stated relationships are true in the experienced range of mean temperature (6-28 °C).

Period emergence - flowering

As other plants of temperate latitudes, *Arabidopsis* goes through a period of vernalization when lower (chilling) temperatures accelerate the generative development. The length of this period could be determined using the multiple linear regression method, where the rate of development between emergence and flowering is treated as a multiple function of mean temperatures of particular days after sowing [4]. The negative regression parameters will indicate the occurrence of the vernalization period; this method requires, however, a great number of data. Using our 133 observations, we concluded that the vernalization is usually completed in 4 days after emergence (Fig. 1). It is known that vernalization in the family *Brassicaceae* can only take place in seedlings and not in seeds [10]. Thereafter, the higher temperatures are needed for speedy development.

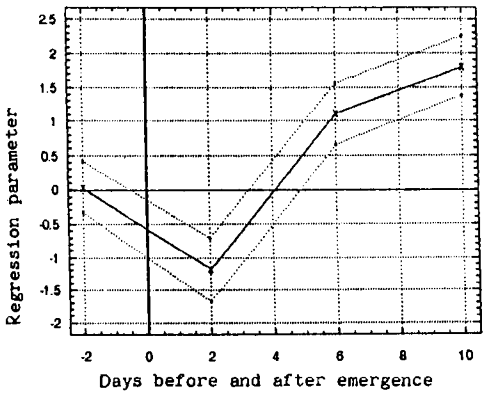

Fig. 1. Partial regression parameters of multiple regression of development rate on mean temperatures in 4-day periods before and after emergence.

Usually the rate of development may be treated as a linear function of mean temperature. However, in the case of *Arabidopsis* this relation seems to be nonlinear (Fig. 2).

We used a concept similar to the 'Ontario method' [2], where the temperature changes in the higher range are less important. We treated all the mean daily temperatures higher than 20 °C as 20 °C; such a modification gave a linear relationship (Fig. 2) and then the temperature summation method could be used.

The duration of the period between emergence and flowering is strongly modified by the photoperiod: therefore the temperature sum depends on daylength (Fig. 3). The relation is:

$$DD = 1694 - 186.9\,P + 5.78\,P^2$$

$$R^2 = 0.41 \quad \text{S.E.} = 26\ \text{DD} \qquad (4)$$

where DD - degree-days calculated between 7 °C (base temperature) and 20 °C, P - daylength in hours.

The relationships may be presented jointly as a multiple function of temperature and

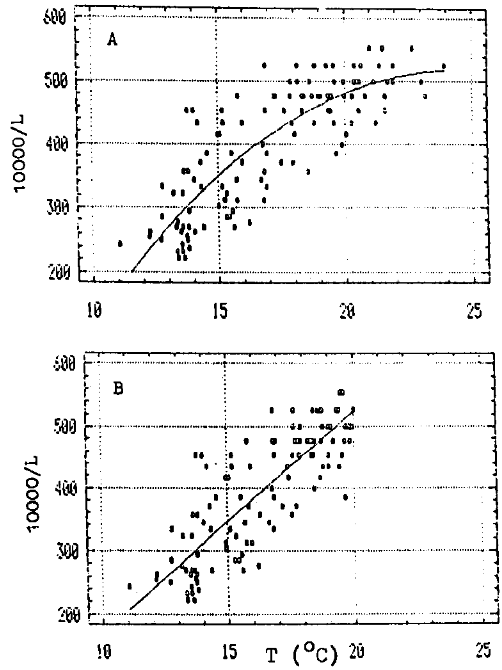

Fig. 2. Rate of development between emergence and flowering as depends on temperature (A). Modification of daily mean temperatures (20 °C limit) gives a linear relationship (B).

photoperiod:

$$L = 406 - 4.1\,T + 0.092\,T^2 -$$

$$42.1\,P + 1.285\,P^2 + 0.16\,Tt_j$$

$$R^2 = 0.94 \quad \text{S.E.} = 1.8\ \text{days} \qquad (5)$$

where L - length of emergence - flowering period (days), T_j - mean temperature of 4 days after emergence, T - mean temperature since 5th day after emergence till flowering.

Figure 4 presents these relations, but disregarding the chilling temperatures.

Period flowering - ripening

The determination of ripening is more difficult than of the other phases, therefore observation errors are probably greater in this case. Using 41 data on ripening the following equation was obtained:

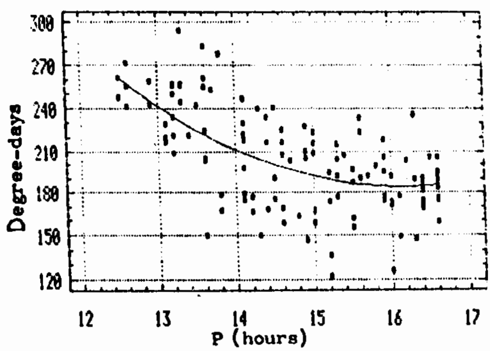

Fig. 3. Degree-days since emergence till flowering (calculated between 7 and 20 °C) as depend on daylength (*P*) at emergence.

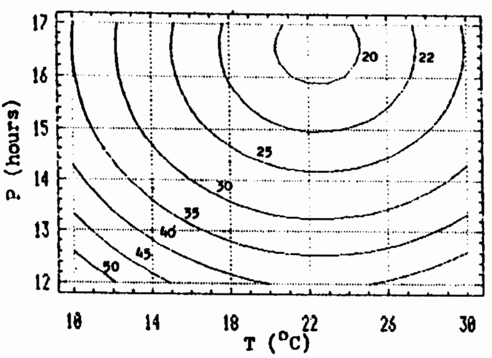

Fig. 4. Duration of emergence - flowering period as depends on mean temperature (T) and photoperiod (*P*) at emergence.

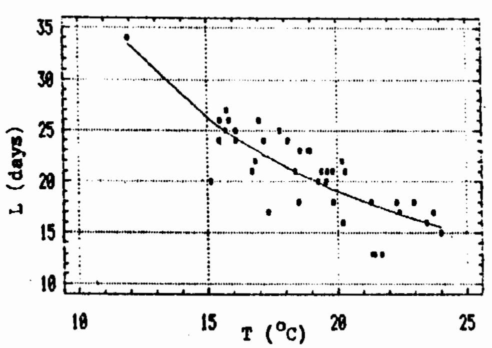

Fig. 5. Duration of flowering - ripening period (L) as depends on mean temperature (T).

$$L = \frac{343}{T-2}$$

$$R^2 = 0.68 \quad \text{S.E.} = 2.5 \text{ days} \qquad (6)$$

This period length does not depend on photoperiod. The dependence of rate of development on temperature may be treated as linear, at least up to 25 °C.

CONCLUSIONS

1. Vernalization during approximately 4 days after emergence accelerates flowering.

2. The relation between temperature and rate of development till flowering must not be treated as linear if mean daily temperatures exceed 20 °C.

3. Under natural spectral composition of light the optimal sequence of temperatures is 15-20 °C after sowing, 1-5 °C during 4 days after emergence, then about 22 °C till flowering and about 25 °C after flowering. The photoperiod between emergence and flowering should be at least 16 h. The life cycle (from seed to seed) lasts under these conditions about 36 days.

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KLIMATYCZNA REGULACJA ROZWOJU *ARABIDOPSIS THALIANA* (L.) HEYNH.

W doświadczeniach wazonowych i polowych obserwowano wschody, pączkowanie, kwitnienie i dojrzewania rzodkiewnika pospolitego (*Arabidopsis thaliana*). Określono ilościowe związki między fenologią a czynnikami klimatycznymi, stosując głównie metody regresji wielokrotnej. Długość okresów między siewem i wschodami oraz między kwitnieniem i dojrzewaniem może być traktowana jako hiperboliczna funkcja średniej temperatury, co pozwala na użycie zwykłej metody sum temperatur. W okresie między wschodami a kwitnieniem zależności są bardziej skomplikowane; zastosowano w tym przypadku pewne modyfikacje metod wiążących rozwój z temperaturą. Krótki okres jaryzacji po wschodach, później zaś wyższe temperatury przy długich dniach przyśpieszają kwitnienie.

Słowa kluczowe: *Arabidopsis thaliana*, fenologia, fotoperiod, jaryzacja, metoda sum temperatur.