MODELLING CARDINAL TEMPERATURES OF COMMON LAMBSQUARTERS GERMINATION BY THERMAL TIME APPROACH

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ABSTRACT

In order to determine the effect of temperature on germination response and cardinal temperatures of common lambsquarters (*Chenopodium album*), germination of common lambsquarters seeds was modelled by the concept of thermal time. Seeds of *C. album*, were incubated to 6 constant temperatures (7, 12, 17, 22, 27 and 32 ºC). Results showed that the temperatures had highly significant on seed germination rate ($P < 0.01$). Among three nonlinear nested sigmoidal regression models (statistical distributions) used in estimate (3 and 4-parameter sigmoidal models and 4-parameter bounded Wibull function), the 4-parameter bounded Wibull model was found to be accurate to describe time course of the cumulative germination of *C.album* seeds at various sub- and super-optimal temperatures. In addition, among three non-linear regression models were fitted to germination rate data in cardinal temperatures of common lambsquarters assessment (triangular, dent-like and beta), the dent-like and beta models resulted the worst fit (with high RMSE amount: 0.0038, 0.0058 and low R^2 values: 0.91, 0.85) respectively. Unlike, triangular model gave the better fit to germinated data ((with less RMSE 0.0028 and high R^2 0.92) and non signifcant obtained *F*- observed= 0.98 from models comparison [triangular versus: dent-like]). Basic temperature of seed germination for common lambsquarters was estimated at 4.58 ºC. Also, the optimum temperature for mid germination rate was found at 20.94 ºC. At the end, ceiling temperature and biological time for 50% common lambsquarters seed germination was determined at 40 ºC and 47.70 hour, respectively.

Keywords: *Ceiling temperature; dent-like model; triangular model; biological time; mid germination rate; wibull function*

INTRODUCTION

The ability to forecast time of weed seedling emergence relative to the crop is an important part of a process-oriented model explaining weed and crop competition. The finale objective of an integrated weed management (IWM) program is to achieve predictability. From an ecological viewpoint temperature is primary environmental signal that, has central role on regulating both seed dormancy and germination. Hence, in many studies, the temperature effect on the seed dormancy dynamic and germination has been tested. Among all stimulator factors of seed germination, temperature and moisture are the most important, that driving germination. In addition, soil temperature and water content are two significant factors that regulate seedling emergence (king and Oliver 1994). Water available is vital in seed imbibition, whereas temperature is closely related to embryo development before germination (Bewely and Black, 1985).

Thermal time (TT), which expressed as function of time refers to the accumulation of heat above a base temperature, is often used as a weather-based index for estimating crop development. Meanwhile, TT in predicting weed emergence is a relatively new approach. To determine the best planning and optimizing the schedule time of weed control, it is needful to find the specific temperatures in each special weed species. These temperatures are known as "cardinal temperatures". Three cardinal temperatures in general describe germination responses to temperature including: the minimum, optimum and maximum. The minimum (or base, T_b) and maximum (or ceiling, T_c) are the both temperatures below and above which germination will not done. In contrast with the optimum (To), is the temperature at which germination is most quick.

In this paper, we hypothesized that the process of germination could be described by the temperature on accumulated thermal time scale (degree-days) and that the radicle elongation changes as a function of temperature.

Common lambsquarters (*Chenopodium album*) is a common weed in worldwide, which can grow well in a broad range of climates and soils. This troublesome weed prospers in disturbed lands rich in organic matter (Mitich 1988). It due to possesses a prolific rooting system, which enable it to survive adverse environmental conditions (Holm *et al*. 1991). The use of TT could help pest managers aimed at interpreting events (*e.g.* germination process) and making timely management decision (Gage 1989). Awareness of *C.album* emergence in response to TT may enable more precise prediction of germination in the field. The main objectives of this research were to examine the effect of temperature on the emergence of *C. album* and to develop a seedling emergence based on accumulated thermal time.

MATERIALS & METHODS

In order to test our hypothesis, incubator study was conducted using seeds of common lambsquarters. A randomized complete block design with three replicates was used to examine the effect of six constant temperature at a range of 7, 12, 17, 22, 27 and 32 °C, at laboratory conditions, Faculty of Agriculture, Mohaghegh-e Ardabili University, Ardabil, Iran, during 2017. For each treatment, 120 seeds of similar size were placed in 9-cm-diameter petri dishes lined with Whatman No.1 filter paper containing 5 mL distilled water. Then these petri dishes were placed in a seed germinator set.

Germination was recorded at about 24-hours intervals until no further germination occurred for 17 days. The seeds were defined as germinated at the time of that the elongated radicles were visible at least 2 mm.

Statistical analysis

All non-linear regression models were evaluated by comparing normalized cumulative emergence value from *C.album* data with the predicted value. Root mean square error (RMSE), was the tool used to make these comparison. Smallest RMSE values indicated that predictions represented observation well. Moreover, for validation test and difference between nested models (*e.g.* full vs. reduced model) was tested statistically. This is accomplished by testing the significant of sum of square reduction between a full and reduced model via calculating the "*F*-observed" as follows (Seber and Wild, 1989).

$$F_{obs} = \frac{(SSRes_{reduced} - SSRes_{full})/p}{MSRes_{full}} \qquad eqn(1)$$

Where *p* is the difference in residual degrees of freedom between the two models, against cutoffs from an *F*-distribution with *p* numerator degrees of freedom. The denominator degrees of freedom equal the residual degrees of freedom in the full model. If the *F*- observed was bigger than the tabulated *F*-distribution (at 5% probability level), with their degrees of freedom, it means that the full model has significantly improved model predictions of the seed germination data.

All statistical distribution parameters were predicted by nonlinear regression (PROC NLIN) that used the Gauss-Newton algorithm in SAS statistic package (Ver. 9.2). Data collected from germination rates experiment was firstly subjected to analysis of variance (ANOVA), to test treatment effects ($P<0.05$). Assumptions and random distribution of residuals for ANOVA, were checked, prior to data were subjected to ANOVA. Data transformation (arcsine square root) did not improved homogeneity of variance. Since, ANOVA for original data were analysed by using PROC GLM in SAS and are presented.

Model development

Three nonlinear nested sigmoidal regression (statistical distributions) including: 3 and 4-parameter sigmoidal models and 4-parameter bounded Wibull function were used to describe time course of the cumulative germination of *C.album* seeds at various sub- and super-optimal temperatures. Overall, models comparison showed that the bounded Wibull function, equation [2] provides better fit, to the pattern of normalized cumulative germination time course.

$$Do\ f(CTT) = 0\ If\ CTT \le t_{mid} + \sigma \times \ln(2)^{\frac{1}{\lambda}}\ Otherwise\ Do:$$

$$f(CTT) = G_{max} \times \left\{1 - \left[Exp\left(-\left(\frac{\left(CTT - \left(t_{mid} + \sigma \times \ln(2)^{1/\lambda}\right)\right)}{\sigma}\right)^{\lambda}\right)\right]\right\} \qquad eqn\ (2)$$

Where CTT, is the cumulative thermal time (on hour scale) t_{mid}, time until middle germination σ, shows distribution of common lambsquarters germination time (germination evenness) λ, is the shape parameter G_{max}, is the maximum germination and as the above conditional statement was established in regarding of above model it called "lag phase".

To predict the pattern of germination time course the cumulative emergence value were compared to accumulated thermal time with the bounded Wibull function. The bounded Wibull function provided, the best fit of germination data, mid germination rate (reciprocal of time to 50% germination) against incubation temperature were estimated. Estimates of time taken for normalized cumulative germination to reach 50% of its maximum at each temperature (which the experiment was conducted), were calculated from the normalized cumulative germination progress curve against times. As well as, germination rate (t_{mid}, per hour) was estimated as equation [3] as follows:

$$GR = \frac{1}{t_{mid}} \quad eqn\ (3)$$

In which GR, is the mid germination rate.

Finally, to estimate the cardinal temperatures in common lambsquarters germination, the rate for 50% germination for each temperature was regressed versus temperature. The effectiveness of several nonlinear regression models encompass triangular, dent-like and beta was parameterized for cardinal temperature. Among these models, triangular regression model equation [4] could best described common lambsquarters germination rate on normalized scale.

$$If\ T_B < T < T_{OR}\ THEN\ DO\ GR_{mid\,(Ti)} = \frac{1}{T_{mid\,(Ti)}} = \frac{\frac{(T-T_B)}{(T_{OR}-T_B)}}{T_{mid\,(T_{OR})}}$$

$$ELSEIf\ T_{OR} < T < T_{CR}\ THEN\ DO\ GR_{mid\,(Ti)} = {}^{1}/_{T_{mid\,(Ti)}} = \frac{\frac{(T_{CR}-T)}{(T_{OR}-T_{CR})}}{T_{mid\,(T_{OR})}}\quad eqn\ (4)$$

$$ELSEIf\ T \le T_B\ OR\ T \ge T_{CR}\ THEN\ DO\ GR_{mid\,(Ti)} = 0$$

In the above function, T_B is the base temperature, T the environment temperatures (the temperature at which the experiment was conducted), T_{OR} the optimum temperature on germination rate for middle percentile, T_C the ceiling temperature on germination rate for middle percentile. $GR_{mid(Ti)}$ germination rate for middle percentile on the ith temperature and $T_{mid(TOR)}$ necessary time until reaching to middle germination at optimum temperature. At the end, others cited models were eliminated to further model development.

RESULTS AND DISCUSSION

The germination time course curve predicted by cumulative thermal time model adequately described the seed germination of common lambsquarters (Figure 1). The predicted germination curve generated by the Wibull function Eqn [2], agreed closely with the observed germination sequence. Maximum final germination percentage was found at 22 ºC. While minimum final germination percentage was found at 7 and 32 ºC (figure 1).

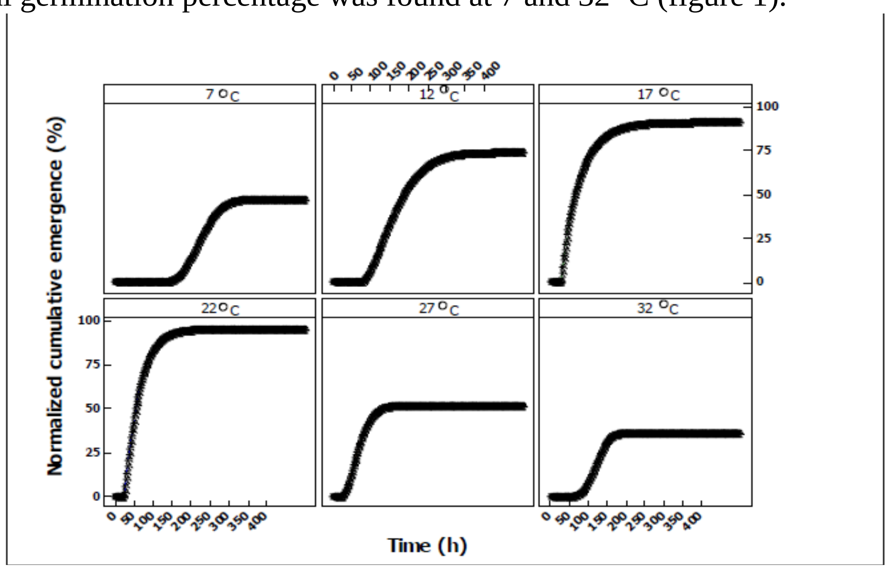

Fig. 1. Time course of the cumulative germination of *C.album* seeds at various sub- and super-optimal temperatures, curves are the predicted germination of the Weibull-based thermal time model (equation 2).

Maximum germination percentage was at 22 ºC. Afterwards a decline in germination was observed with declining and increasing temperatures (figure 1). This trend of cumulative germination percentage shows trend of germination over time course and chiefly final germination percentage that could help to understand the effect of temperature on seedling emergence in farmlands, and making farmers to have timely management decisions. Non-linear regression models have been used to describe relationships between germination rate and temperature. Other researchers have been used such regression models for quantifying germination responses and plant seed germination against temperature (Mwale *et al.* 1994; Kebreab and Murdoch 1999).

The effect of temperature on germination rate of common lambsquarters was highly significant ($F_{5,12}$=12.03, p≤0.01). Rates of radicle emergence were regressed against temperature (figure 2). Germination rate (for 50% percentile germination) varied with incubating time course (figure 2). A increase and then decline in germination was observed with increasing temperature (figure 2). Estimates of cardinal temperatures were varied 4.58, 20.94 and 40 ºC for base, optimum and ceiling temperatures, respectively. Furthermore, the predicted biological time (on hour scale) to seed emergence generated by Eqn [4], agreed closely (table 1), with the observed germination sequence, fitted to the Weibull function Eqn [2].

Beta model due to model comparison, outlier parameters estimate and non-significant parameters was not suitable candidate in further model development. Since the triangular model was selected as the superior model (RMSE =0.0028, R^2=0.92 and non-significant obtained *F*-observed= 0.98 from models comparison [triangular versus: dent-like]), in cardinal temperatures prediction. Cardinal temperatures for germination process were determined by triangular procedure described for germination, and only its parameters were presented here (table 1). In contrast with, germination did not occur below 4.58 and more than 40 ºC. On other hand, maximum germination was occurred at 20.94 ºC (figure 2).

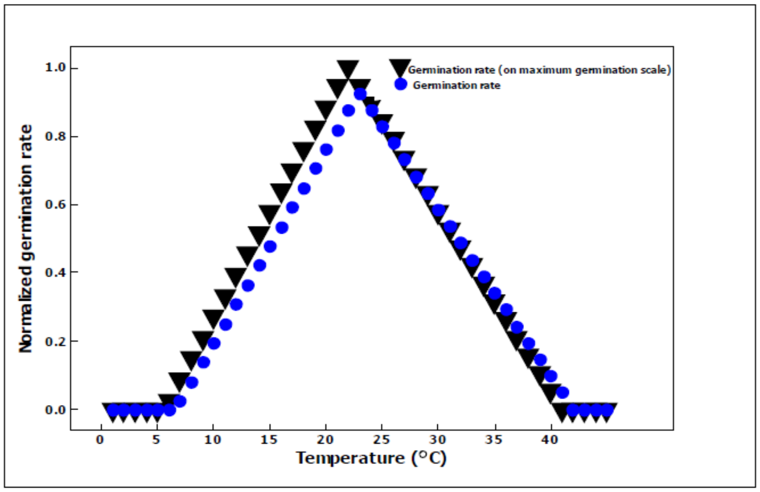

Fig.2. The effect of temperature on mid germination rate (on normalizes scale), using the triangular model in *C.album* (equation 4). Model parameters are shown in table 1.

in accordance with our research, Vleeshouwers (1997), observed that maximum emergence of common lambsquarters seedling from a depth of 0.5 cm occurred at a temperature range of 20 to 25 ºC. Moreover, optimum temperature of common lambsquarters germination was revealed 24 ºC (Harvey and Forcella 1993). Moreover, optimum temperature of germination was revealed 24 ºC, in this weed (Murdoch *et al*. 1989).

Table 1. Estimation of Cardinal Temperatures, Biological Time of Common lambsquarters Germination and 95% Confidence Intervals.

Parameters (Cardinal Temperatures)	Estimate	e.s.e.†	Lower bound	Upper bound
Base Temperature	4.58	(2.60)	-6.62	15.78
Optimum Temperature	20.94	(2.02)	12.22	29.66
Ceiling Temperature	40	(4.88)	19.00	60.99
Biological Time = ($T_{mid(Tor)}$) [h]	47.70	(5.38)	24.53	70.87

† e.s.e., estimated standard error.

Other researchers who studied germination as a function of temperature reported that no germination of common lambsquarters occurred below 4 ºC (Harvey and Forcella 1993). The lack or reduction in germination rate at unfavourable temperatures can attributed to reduction or inhibition of enzymatic activity (Kamaha and Magure 1992). Meanwhile, another mechanism for this event is reduced metabolic efficiency at super-optimal temperatures (Thygerson *et al*. 2002).

Although, the outcomes of our study confirmed that, in the lacking of other environmental cues, the germination of *C.albom* seeds was greatly influenced by temperatures in laboratory conditions. As well as, model validations revealed that the triangular model of germination rate accurately determine the cardinal temperatures in *C.albom*. In conclusion, the simplicity and goodness of fit provided by this model offer notable potential for predicting germination and seedling emergence in field situation where temperature vary in an unpredictable factor. For ecological implication, these models must, however, be tested in the stimulated field data.

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