Industrial Crops and Products 35 (2012) 192–198

Contents lists available at ScienceDirect

Industrial Crops and Products

journal homepage: www.elsevier.com/locate/indcrop

Quantification of the cardinal temperatures and thermal time requirement of opium poppy (*Papaver somniferum* L.) seeds to germinate using non-linear regression models

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ARTICLE INFO

Article history:
Received 30 March 2011
Received in revised form 25 June 2011
Accepted 28 June 2011
Available online 26 July 2011

Keywords:
Base temperature
Germination rate
Temperature response
Modeling
Thermal time

ABSTRACT

The response of plant development rate (including germination rate) to temperature might be described as a non-linear function. We compared 3 non-linear regression models (Dent-like, segmented and beta) to describe the germination rate-temperature relationships of opium poppy (*Papaver somniferum* L.) over 6 constant temperatures to find cardinal temperatures and thermal time required to reach different germination percentiles. Two replicated experiments were performed with the same temperatures. An iterative optimization method was used to calibrate the models and different statistical indices (mean absolute error, coefficient of determination (R^2), intercept and slope of the regression equation of predicted vs. observed germination rate) were applied to compare their performance. The segmented was found to be the best model to predict germination rate (R^2 = 0.92, MAE = 0.0011 and CV of 1.4–3.6%). Estimated cardinal temperatures were similar for different germination percentiles (P < 0.05). Base on the model outputs, the base, the optimum and the maximum temperatures for germination were estimated as 3.02, 27.36 and 36.31 °C. The thermal time required to reach 50 and 95% germination was 57.27 and 87.55 degree-days, respectively. Model predictions of the time required for seed germination agreed reasonably well with the observed times (MAE = 0.56 day, R^2 = 0.887). All model parameters may be readily used in crop simulation models.

1. Introduction

Seed germination is a complex biological process that is influenced by various environmental and genetic factors (Shafii and Price, 2001) and is considered as one of the most critical periods in the life cycle of plants (Ungar, 1978). Environmental conditions directly surrounding a seed determine germination success and subsequent seedling emergence and establishment (Harper, 1977). Temperature and water mainly drive the rate of seed germination when aeration is not restrictive (Gummerson, 1986a,b). When moisture is adequate, both the rate and final fractional germination of a sample of viable seeds are controlled by temperature (Dubertz et al., 1962; Heydecker, 1977; Bierhuzen and Wagenvoort, 1974). Temperature is the most important driving force influencing crop development rate (Kamkar et al., 2008). The effects of temperature on plant development are the basis for models used to predict the timing of germination. Three cardinal temperatures (base, optimum and maximum) describe the range of temperature over which seeds of a particular species can germinate (Bewley and Black, 1994). Estimation of the cardinal temperatures is essential because rate of development increases between base and optimum, decreases between optimum and maximum, and ceases above the maximum and below the base temperatures (Mwale et al., 1994; Shafii and Price, 2001).

For most crop plants, the response of germination rate to temperature can be simplified to a bilinear response. There is usually a positive linear relationship between the rate of germination (defined as the reciprocal of the time taken for a given fraction of the seed population to germinate) and temperature (T), up to a well-defined optimum temperature (T_o) (Hegarty, 1973). Studies on seeds of different crops have shown that above T_o there is a negative

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doi:10.1016/j.indcrop.2011.06.033