

Evaluation of a Metabolic Cotton Seedling Emergence Model

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Received 29 May 2015; accepted 13 July 2015; published 16 July 2015

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Abstract

A model for cotton seedling emergence (MaGi) based on malate synthase kinetics was evaluated. Cotton seeds were planted through the early spring and into typical planting times for the areas. Soil temperatures at seed depth were used as inputs into MaGi and a commonly used seedling emergence model based on heat unit accumulation (DD60). Time to 50% emergence was calculated and compared with predicted emergence using MaGi and DD60. MaGi yielded predictive capability without the need to resort to lengthy experimentation required by traditional methods. The results suggest that a physiological or semi-empirical approach incorporating both enzyme kinetics and whole plant temperature responses would be useful for rapidly constructing seedling emergence models.

Keywords

Cotton, Seed, Emergence, Degree Day, Crop Model

1. Introduction

The environment influences seedling emergence through biotic and abiotic factors. Biotic factors include such as presence or absence of soil pathogens, nematodes, bacteria, or fungi affect survival of seedlings during or shortly after emergence. The effects of biotic factors on seedling emergence vary greatly from site to site and are very difficult to predict with certainty, other than to make broad generalizations; for example, the observation that when the soil is cold and wet for an extended period of time seeds succumb to fungal or bacterial infection. The effects of abiotic, or physical factors are much more predictable. The effects of abiotic factors such as soil temperature and moisture on developmental seedling processes have been empirically studied for nearly a century. Such studies have resulted in fairly robust predictive models based upon empirically derived data sets. The most

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often used models of seedling emergence are based upon simple linear models of growing degree day (GDD) accumulation, though some curvilinear emergence models have been described [1]. Some models, also painstakingly empirically developed, exist which incorporate soil moisture as well as temperature. These hydrothermal seedling emergence models have been developed for both crop and weed species (e.g. [2] [3] and references therein) but have seen rather limited use, at least in agronomic enterprises, perhaps because of the difficulty of obtaining soil moisture inputs across soil types as compared with the ease with which soil temperatures are obtained. Moreover, other confounding factors exist which limit such model utility such as differences in observed imbibition rates perhaps due to variation in soil-seed contact, especially with smaller seeds or coarser soils [4] [5].

That seedling emergence is a singularly important event in annual plant development especially with regard to survival, reproductive success, or crop production has led to the recognition that generally applicable mechanistic models of seedling growth and development are needed to that critical stage of emergence [4]. Seedling development results from sequential developmental processes resulting in defined phenological events from a regulated suite of underlying physiological processes. The complexity of this process explains, at least in part, why little progress has been made towards physiological modeling of crop seedling development, and why such modeling approaches have been, almost without exception, empirical. Virtually no mechanistic physiologically based seedling development models exist, with perhaps one notable exception [6].

To the authors' knowledge, a single physiologic model of cotton seedling development has been described. This model of cotton seedling development, MaGi, is a dynamic metabolic cotton seedling emergence model based upon the calculated thermal dependence of the malate synthase reaction velocity in developing cotton seedlings. The theory behind the model is that seedling growth and expansion is limited by food and osmolyte, respectively, and that the primary limiting process in seedling emergence is the enzymatic catabolism of stored photosynthate into metabolically and osmotically active moieties. Briefly, the model is based on the assumptions that in developing cotton seedlings: 1) malate synthase reaction kinetics are temperature dependent [7]; 2) the calculated Michaelis-Menton reaction velocities of malate synthase are proportional to the relative seedling emergence rates [8]; 3) a threshold value of reaction product is required for seedling emergence [6]; and 4) under near ideal conditions cotton seedlings typically emerge in about three days (personal observations of growth chamber grown plants). The structure of the model is shown as a flow diagram or decision tree in Figure 1. The model itself simply looks up the relative calculated throughput at each measured soil temperature and integrates the relative reaction product over time. If the reaction product accreted over the interval is not greater than a threshold value, that value expected for a three-day period at optimal seedling development temperature, then additional time is added to the time interval and the process repeated until the threshold value is reached.

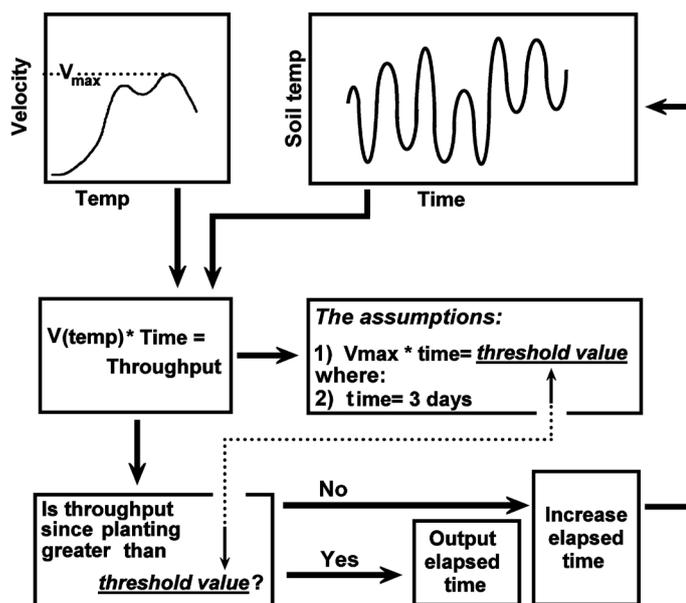


Figure 1. Diagram depicting schematic and selected assumptions of MaGi metabolic cotton seedling emergence model [6].

Herein we present the results of a study that designs to investigate the predictive capability of MaGi under a variable soil temperature regime in agronomic setting.

2. Methods

The experiments were carried out in the field at the USDA-ARS facility in Lubbock, TX over three months during a single Spring planting season. The soil at the facility is an Amarillo fine loamy mixed superactive thermic sandy-loam, Aridic Paleustalf. These soils have relatively high Ca and Mg carbonate content, $\text{pH} > 7$, extremely low organic (carbon) content ($< 2 \text{ g}\cdot\text{kg}^{-1}$), and are classified as moderately permeable. The soil was prepared by tilling in early spring, then, one day prior to planting the soil was moistened. At planting the soil was tilled again, raked level, and 50 holes made by pressing a peg board against the soil surface. The peg board was a $5 \text{ cm} \times 30 \text{ cm} \times 40 \text{ cm}$ laminated board with a $5 \text{ cm} \times 10 \text{ cm}$ regular rectilinear array of 4 cm long pegs spaced at 7.5 cm. After pressing the pegs into the soil surface and removing the board, a single cotton (cvar. DP 444) seed was placed into each hole, and the plot was evenly covered to a depth of 0.5 to 1.0 cm of soil, lightly tamped and irrigated daily after planting with water from the municipal supplies, in an attempt to keep the soil at or near field capacity and so remove water potential differences as a source of variability in seedling emergence rates. Plots were planted twice weekly. The number of emergent cotton seedlings were counted daily and the date of 50% emergence was determined graphically.

Soil temperatures at seed depth from each plot were recorded using waterproof thermistor probes (Model TMCx-HD, Onset¹ Computer Corp.; Pocasset, MA; <http://www.onsetcomp.com>) connected to an Onset Computer Corp. HOBO model U12 outdoor industrial data logger. Soil temperature was recorded at 5 minute intervals and used to drive the dynamic cotton seedling emergence model [6]. Daily maximum and minimum temperatures were used to calculate seedling emergence based on a commonly used empirically derived linear cotton seedling emergence model, DD60, based on heat unit accumulation [9]. Ambient air temperatures were not presented or evaluated because it soil temperature was the driver of both models. Nevertheless environmental conditions were recorded by a weather station located on site (<http://www.lbk.ars.usda.gov/wewc/weather.aspx>).

For presentation, the model was run unchanged since the original report when the initial assumptions were made and the first iteration of the model was written [6]. No attempts were made to force or adjust the model to better fit observed results.

Soil temperatures during the experiment were plotted graphically with the dates of planting and the periods of time each cohort existed as pre-emergent plants indicated. Predicted and actual days to 50% emergence were plotted against model results of MaGi run at 0.25 day increments and of DD60 at 1 day intervals. Outputs from both models were compared to actual emergence by linear regression and RMSE (Root Mean Square Error) calculated as the square root of the averaged squared error about the actual emergence values.

3. Results

A graphical representation of soil temperatures, planting dates, and times to 50% emergence is shown in **Figure 2**. Soil temperatures are depicted by a solid continuous sinusoidal black line. The planting dates, as Day of Year (DOY), are indicated by the small green triangles along the time (DOY) axis. The green horizontal lines above the soil temperature data represent the time to 50% emergence of individual cohorts of seeds. The line segments begin and end on the planting date and the 50% emergence date, respectively. Over the duration of the experiment, that is, from the planting of the first cohort (DOY 64) to the observed 50% emergence of the final cohort (DOY 147) soil temperatures at planting depth ranged from -0.5° to 37.5° . These soil temperatures varied diurnally and seasonally and ranged from atypically cool to typical for the location during cotton planting times as compared to soil temperatures recorded over the past several years by a station located within 400 meters of the plots used in this study (<http://www.csrl.ars.usda.gov/wewc/weather-pswc-data.aspx>). Daily soil temperature variation was generally on the order of $15^\circ - 20^\circ$, comparable to those typically encountered in the region. The first 13 cohorts were planted over a 44-day period emerged over a 2-week period. In these early cohorts emergence was not entirely sequential, that is, some earlier planted cohorts achieved 50% emergence after later planted cohorts. This was associated with fewer seedlings surviving to emergence (not shown). As soil temperatures warmed in mid- to late-April 50% emergence of the cohorts was sequential; that is cohorts emerged in the

¹Mention of trade names or commercial products in this publication is solely for the purpose of providing specific information and does not imply recommendation or endorsement by the U.S. Department of Agriculture.

order of planting. As soil temperatures increased during the spring, the time to emergence decreased. Other than these observations no clear relationship could be discerned from these data.

Visual inspection of **Figure 3** reveals that the MaGi model results yield higher temporal resolution as compared to the DD60 model since the DD60 model used a daily time step whereas MaGi used a 0.25 day time step. This is seen as a finely jagged line with the MaGi model as compared to the smoother DD60 model's plotted output. At later planting dates, when the soil was warmer and time to emergence was shorter, the DD60 model more closely approximated observed emergence. With earlier planting dates, and longer times to emergence (**Figure 2** and **Figure 3**) MaGi was apparently a better predictor of time to 50% seedling emergence (cooler soil temperatures) while DD60 exhibited better predictive capability at later dates (warmer temperatures) (**Figure 4**). This is reflected in the intercept values of the two models (**Figure 4**) though overall model response (slopes) were nearly identical ($Slope_{DD60} = 0.68$, $Slope_{MaGi} = 0.70$).

4. Discussion

Early seedling emergence models used a growing degree day (GDD) approach. This approach is still commonly used to this day [9]. In its simplest form, a GDD is difference between the average daily temperature and an empirically determined "base temperature". The MaGi model of cotton seedling emergence differs from GDD models in general, and from the DD60 model in particular in several respects. First, a GDD model is based on a linear [temperature] × [time] function upon which phenological events are empirically imposed. MaGi is based on calculated temperature dependent reaction throughput, from which phenological events are assumed to result.

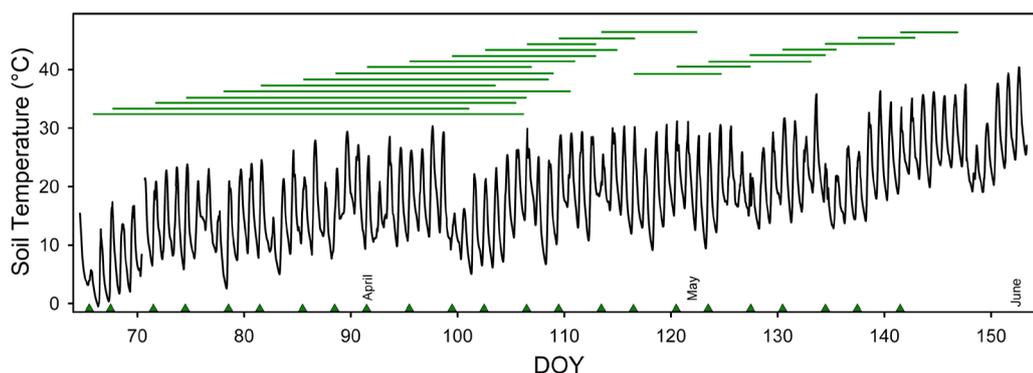


Figure 2. Soil temperatures (solid black line), planting dates of cohorts (triangles), and time seeds of each cohort remained in ground until 50% emergence (green bars at top of figure).

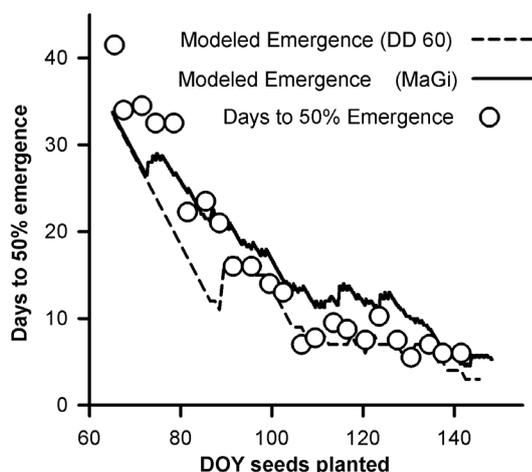


Figure 3. Predicted time from planting to emergence for cotton as determined from the malate synthase based model (MaGi, solid line), compared to a model based on accumulated heat units (DD60, dotted line). Open circles show actual days to 50% emergence.

Another difference is that MaGi is a continuous function where the rate of GDD accumulation is frequently a discontinuous function with respect to temperature. There are two approaches to refine estimates of GDD. The first is to increase the temporal resolution of the heat unit calculation, usually by using daily maximal and minimal temperatures and making assumptions about the sinusoidal characteristics of diurnal temperature variation [10] [11]. The other approach is to modify the function through which heat units accumulate. For example heat unit accretion could be set to zero if average temperature is below the base temperature so that the daily value cannot be negative, *i.e.* that accrued heat units cannot be lost [12]. A temperature ceiling might also be introduced so that if temperatures exceed given value, then heat units would not accumulate beyond a maximal rate, or heat units might even accumulate at a lesser rate beyond a certain temperature resulting in a segmented, discontinuous model [1]. Such segmented models can result in differences in model output between workers with the same temperature inputs [12]. MaGi circumvents this by being driven by a smooth non-linear enzyme reaction curve across the temperature range, which can be described by a continuous differentiable mathematical function.

Both models used in the present study yielded similar predictive capability over the entire range of conditions investigated, though the DD60 was less able to predict emergence times at low temperatures (**Figure 3** and **Figure 4**). We attribute this to the difference in the model approach, the DD60 model assumes no GDD accumulation below a threshold temperature whereas MaGi has no need for a base temperature and simply assumes a slower reaction rate. MaGi was less able to predict seedling emergence at higher temperatures, but this can easily be addressed by revising the assumption of the minimal time required for emergence at optimal temperature. It should be borne in mind that in these experiments MaGi was run as initially conceived and as initially described without any modification [6].

The model described herein and elsewhere [6] is based on the malate synthase reaction velocity, an enzyme that exhibits changes of up to 23,000% activity in developing oilseeds. Conceptually, MaGi was borne from the assumption that the enzyme mediated reaction rate would be useful as a relative indicator of material available for cell wall synthesis and osmolyte to drive growth as cell expansion. This is supported by **Figure 5** which shows that the modeled malate synthase reaction velocity is quite similar to hypocotyl expansion rates described more than a half century ago [13] and is also consistent with the temperature optimum for seed emergence rate reported by Wanjura and Buxton [14]. Perhaps most remarkable about the plots in **Figure 5** is that the shoulder in relative reaction rate predicted used by MaGi [6] is also seen in purely empirical hypocotyl elongation data reported by Arndt over a half century ago [13]. The physiological assumptions of MaGi [6] provide a hypothetical mechanism for this observation, which could otherwise be considered anomalous [13]. Similar hypocotyl expansion could now be less laboriously generated by growing seedlings in devices such as gradient temperature plates, perhaps with modifications specifically engineered for such purposes [15] [16]. This is significant because this suggests that a semi-empirical approach might be used to more rapidly generate seedling emergence models perhaps employing analysis of enzyme kinetics for initial model generation, *in vitro* investigation of seedling development under temperature gradients to check assumptions, finally followed by field validation.

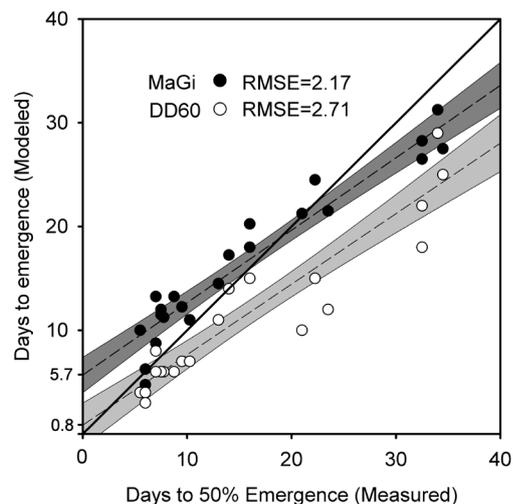


Figure 4. DD60 and MaGi model results compared to observed time to 50% emergence.

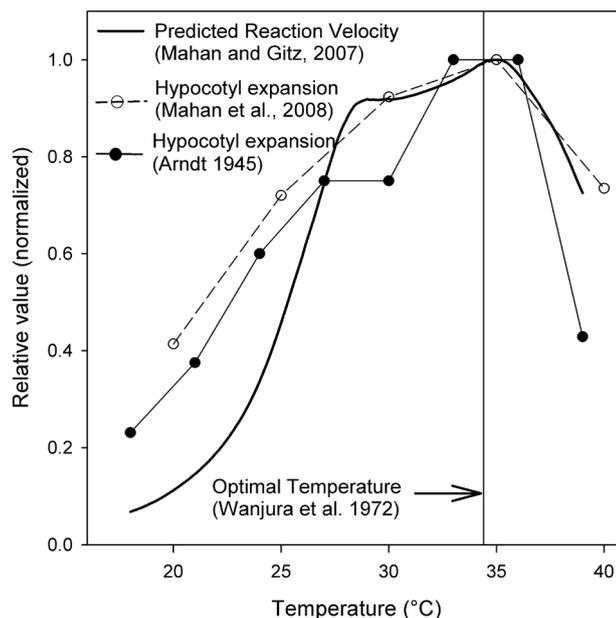


Figure 5. Normalized plots of effect of temperature on calculated malate synthase velocity in cotton seedlings [6], the effect of temperature on hypocotyl expansion rate [13] and the experimentally determined optimal temperature for cotton seedling emergence [14].

5. Conclusion

To our knowledge exactly one mechanistic physiologically based model of seedling emergence exists. This model, MaGi, demonstrates an alternate approach to modeling seedling emergence without resorting to the purely empirical determination of base temperatures and accretion of thermal units. Rather than using maximal and minimal temperatures for estimation of daily thermal effects on emergence, MaGi uses directly measured soil temperature as an input. The GDD based model provided better predictive capability closer to typical planting times and temperatures, but this version of MaGi was unchanged from the original model and has not been refined from the original assumptions. Although GDD models might be easier to understand and apply by growers, GDD and MaGi gave comparable results; so that MaGi might be used to derive GDD models. This physiological approach to seedling emergence modeling is a significant departure from other approaches and may prove useful in the development of emergence models for other crops and in other agronomic research endeavors.

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