# A Systematic Method For Studying Seedling Emergence

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## Abstract

A systematic procedure is outlined for developing seedling emergence models. A model was formulated to describe cottonseed water-uptake during imbibition and hypocotyl elongation until emergence from the soil. Laboratory experiments were used to define the values of environmentally-dependent coefficients of selected soil parameters in the model, on which germination and emergence depend. In validation tests, the model predicted radicle emergence time within ±9%, and predicted time-wise hypocotyl elongation was not significantly different from observed values in 9 of 10 comparisons. The sensitivity of emergence to individual soil environmental parameters was quantified using simulation. A procedure for estimating maximum expected emergence for optimum soil environments was developed from model simulations and verified in field tests.

## Introduction

The cost of planting and establishing a stand is a small part of the expense for producing a crop. However, the influence of the seedling stand in determining yield potential far outweighs its cost of establishment. The condition of the seedling stand is the initial state of the system which ultimately produces the yield of the desired commodity. The potential of the crop after stand establishment cannot be easily manipulated to increase its productive capacity above that of the beginning stand. These considerations emphasize the importance of using the best available technology to provide a soil environment which causes uniform seed germination and seedling emergence and results in a vigorous stand of seedlings.

## Systems Approach

The scientific method (1)[2] is a proven and accepted procedure for formulating and testing hypotheses. A relatively new procedure in which the output of a system is studied as it responds to inputs is

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[2] Numbers in parentheses refer to literature cited.

the systems approach. This approach usually includes formulation and evaluation of a model which is intended to represent the system. Thus in the context of the scientific method, the formulation of a model is analogous to developing a hypothesis. Assuming that the hypothesis is generally more specific than the model resulting from the systems approach, a model is likely to provide more information about the overall system than that derived from a hypothesis.

The power of the systems approach makes it an excellent tool for studying seedling emergence. There is an abundance of empirical data on the influence of various soil and meterological parameters on seed germination and seedling emergence for the major agronomic crops grown in the United States. Although specific numerical relationships between independent variables and seedling emergence may not be available for all crops, there is sufficient information to determine the factors limiting seedling emergence. Thus, the necessary information to develop seedling emergence models is available or the proper experiments can be designed and conducted to obtain the information.

## Suggested Approach

A suggested procedure to use in developing a seedling emergence model follows:

(a) Analyze the seedling emergence system
(b) Identify the independent factors limiting seedling emergence
(c) Formulate a conceptual model of the seedling emergence system
(d) Develop the necessary numerical relationships between independent factors and seedling emergence
(e) Develop the computer code for the conceptual seedling emergence model
(f) Verify the seedling emergence model
(g) Investigate the seedling emergence system by simulation with the model

As an example of this procedure, a cotton (*Gossypium hirsutum* L.) seedling emergence model was developed using the procedure outlined above. The same procedure can be used to develop seedling emergence models for other crops, including sugarbeets. Steps c, d, f, and g will be emphasized.

## Conceptual Model

Cotton emergence is considered to occur in two phases. The first phase (radicle emergence) extends from planting until radicle length of the seedling population averages 3 mm. The second phase (hypocotyl elongation) begins with radicle emergence and continues until hypocotyl emergence from the soil.

Phase I is primarily dependent on water absorption by the seed, and water status is used to indicate germination progress. This phase considers inputs of soil temperature and soil-moisture tension at seed level. Phase II considers inputs of soil temperature, moisture tension, and physical impedance above the seed.

Seed water-content and seedling elongation were measured experimentally using a combination of inputs held at various constant levels. Temperature effects were evaluated between 12.8°C (55°F) and 37.8°C (100°F), moisture tension between 0.3 and 10 bars, and physical impedance between 0.23 and 3.36 kg/cm$^2$. In Phase I experiments, the time variation of seed moisture-content was measured between planting and the 3-mm radicle emergence event. Phase II experiments began when radicles of germinated seeds averaged 3-mm in length and continued until 50 percent of the seedling hypocotyls emerged from a 7.5-cm planting depth. A more complete discussion of the procedure and data obtained to develop the mathematical relationships for modeling Phases I and II is given elsewhere (3, 4).

*Phase I – Mathematical Definition*

The rate at which seeds imbibe water is dependent on the difference between actual and steady-state seed water-content. This is expressed as:

$$\frac{dW}{dt} = \frac{1}{T}(W_S - W) \qquad [1]$$

where:

$\frac{dW}{dt}$ = Rate of seed-water uptake

$W_S$ = Steady-state level of imbibitional water in seed

$W$ = Accumulated imbibitional water content of the seed at time (t)

$T$ = Time constant which reflects the total resistance to water absorption by the seed

The lumped constant, T, represents all seed-soil system resistances to water uptake as influenced by soil temperature, soil moisture, seed coat, and internal seed constituents. The value of T is indicative of seed-water uptake rate.

By rearranging terms, equation [1] can be represented in standard form.

$$T \frac{dW}{dt} + W = W_s \qquad [2]$$

Solution of equation [2] for a step input, constant T, and initial seed moisture, $W_o$, is:

$$W = W_s + (W_o - W_s) \exp(-t/T) \qquad [3]$$

The general shape of equation [3] is a logarithmic curve which has a rapid rise in its early phase and then becomes asymptotic to a steady-state value.

Seed-water content can be predicted if values for $W_s$, $W_o$, and T are known. The values of $W_s$ and $W_o$ were determined experimentally. Measurements of seed-water uptake from the radicle emergence tests were employed to obtain estimates of T.

The value of T for each treatment level was calculated using the least squares criterion. The sum of squares of the differences between the natural logarithm $(W_i - W_s)$ and the natural logarithm $(W_o - W_s) \exp(-t/T)$ was formed. $W_i$ is the observed value of seed-water content. By taking the partial derivative of the resulting expression with respect to T and equating to zero, T is estimated. This procedure results in equation [4] where discrete time values are indicated by $t_i$.

$$T = \frac{\Sigma t_i^2}{\ln(W_o - W_s)\Sigma t_i - \Sigma \ln(W_i - W_s)t_i} \qquad [4]$$

The values of T from each treatment were used to obtain the regression equation [5] which defines 1/T as a function of soil temperature and moisture tension.

$$\frac{1}{T} = 0.033776 + 0.000086S^2 - 0.003479M \qquad [5]$$

S = Soil temperature, °C

M = Soil moisture, bars

The magniture of T is greatest at combinations of low temperature and high soil-moisture tension. Temperature has more influence on T than does moisture within the range of values studied.

*Phase II – Mathematical Definition*

Hypocotyl elongation before emergence is limited by the quantity of stored energy in the seed and the condition of the soil environment. Hypocotyl growth results from cell division and elongation which is not confined to a single region. This pattern of growth results in exponential elongation with a later diminishing growth rate as the stored energy in the seed is depleted. The overall hypocotyl elongation pattern or a constant environment results in a sigmoid curve described by equation [6].

$$\frac{dE}{dt} = KE\,(E_s - E) \qquad [6]$$

where:

$\frac{dE}{dt}$ = Rate of hypocotyl elongation

$K$ = A constant

$E$ = Elongation at time (t)

$E_s$ = Maximum possible elongation in a constant environment

The quantity of unused energy at any time (t) is represented by $E_s - E$. During growth, the rate of increase slows as the maximum size is approached. Based on the mathematical description, the elongation rate is small at first because E is small. Elongation rate decreases as E approaches $E_s$ due to the decreasing difference between $E_s$ and E. dE/dt is greatest for intermediate values of E.

The solution of equation [6] for constant conditions is:

$$E = \frac{E_o E_s}{E_o + (E_s - E_o)\exp(-KE_s t)} \qquad [7]$$

$E_o$ is hypocotyl elongation at time zero and t represents time. The product, $KE_s$, is dimensionally analogous to 1/T in equation [1]; both have dimensions of time.

Hypocotyl elongation was measured for a number of constant environmental conditions (4). All terms in equation [7] except $E_o$ and K were measured. A value of 0.05 mm was selected as a good estimate of $E_o$ based on trial and error. Values for K were determined by using a logarithmic transformation of the non-linear equation [7] to obtain the linear form.

$$\frac{\ln\left(\frac{\frac{E_oE_s - E_o}{E}}{E_s - E_o}\right)}{tE_s} = -K \qquad [8]$$

Linear regression analysis was used to estimate the K for each environment.

*Percent Emergence*

Percentage of emerged seedlings was calculated from a set of regression equations. These equations were developed from experimental data that relate mean hypocotyl elongation and soil-moisture tension to the percentage of seedlings whose lengths exceed specific planting depths. The flow chart for the complete cotton emergence model is shown in Fig. 1.

## Model Verification

The emergence model received validation for Phase I, Phase II, and percentage of seedling emergence.

*Phase I – Radicle Emergence*

The results of using the radicle emergence portion of the model to predict the 3-mm radicle extension event are shown in Table 1. The first four comparisons were taken from a field planting; the last two from tests conducted under ambient temperatures in the greenhouse. The deviations between predicted and observed values are less than 10%. A partial explanation for the deviations is that radicle emergence is a continuous process and the model is discrete (1-hour time steps). The environment is treated as a constant during each interval and the coefficient (T) for the period is changed based on the input. The suitability of the soil environment during each time step for germination is reflected in the magnitude of T equation [5].

*Phase II – Hypocotyl Elongation*

The results from simulating hypocotyl elongation under fluctuating temperatures are shown in Table 2. The procedure for estimating the goodness-of-fit was to calculate a linear regression between observed and predicted values. The linear regression coefficients have a value of 1.0 if the model is unbiased. The model was significantly biased in only one of 10 comparisons. The standard error of the estimate was less than 10% of maximum length, except for the last comparison which approached 20%.

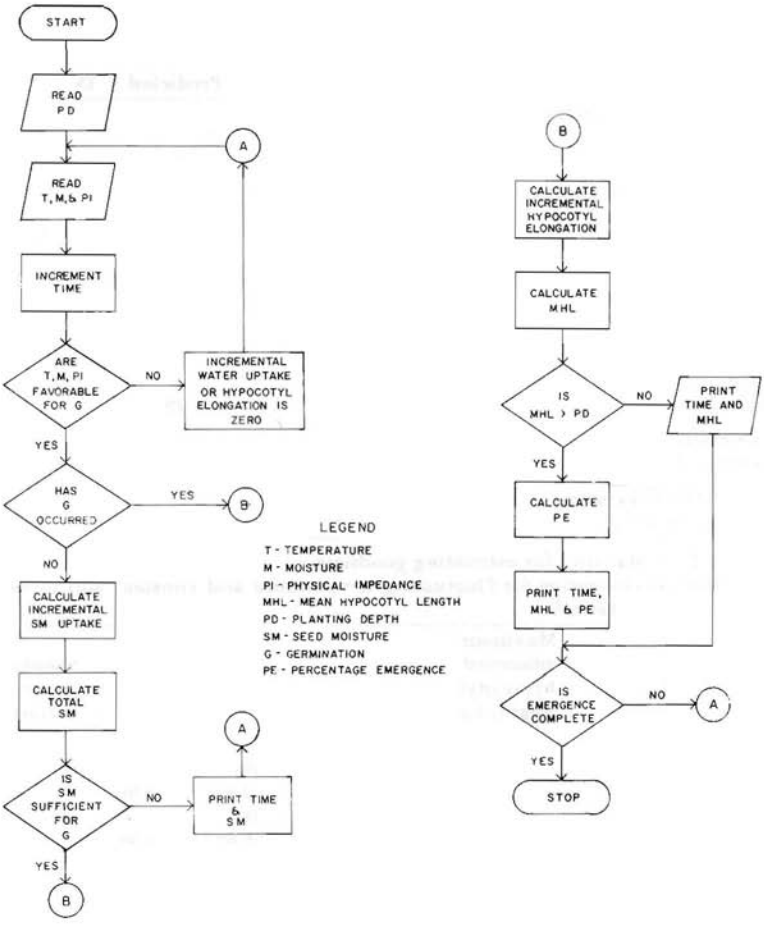

**Figure 1.—Flow chart for cotton germination and emergence model.**

*Field Emergence Percentage*

Field emergence tests were conducted during the 1970-71 growing seasons over a wide area of the Cotton Belt by cooperating researchers in Regional Project S-69. Soil temperatures were recorded hourly in the seed zone. Soil moisture was sampled in the seed drill from planting depth to 1.3 cm below. A penetrometer with a blunt, 0.4-cm-diameter probe was inserted at the soil surface and pushed to seed depth. The accumulated resistance registered by the penetrometer was used as the measure of physical impedance. Soil moisture and

**Table 1. — Comparison of Observed and Predicted 3-mm Radicle Emergence Times Under Fluctuating Environmental Conditions.**

| Description of soil environment | Time-hours | | Deviation,%' |
|---|---|---|---|
| | Observed | Predicted | |
| 2.5-cm planting depth, fluctuating temperature, 7-25°C, Moisture, 0.3-0.8 bars | 65 | 71 | +9 |
| 5-cm planting depth, fluctuating temperature, 9-24°C, Moisture, 0.3-0.8 bars | 76 | 73 | 4 |
| 7.5-cm planting depth, fluctuating temperature, 10-25°C, Moisture, 0.3-0.9 bars | 79 | 73 | -8 |
| 10-cm planting depth, fluctuating temperature, 12-26°C, Moisture, 0.3-0.8 bars | 78 | 72 | -8 |
| 0.3 bars moisture, fluctuating temperature, 25-33°C, | 24 | 23 | 4 |
| 0.3-bars moisture, fluctuating temperature, 26-32°C, | 25 | 25 | 0 |

**Table 2. — Statistics for estimating goodness-of-fit between observed and simulated hypocotyl elongation for fluctuating temperature and constant soil moisture and physical impedance*.**

| Description of soil environment† | Maximum observed hypocotyl length, cm | Coefficient | T-value | $R^2$ | Standard error of estimate |
|---|---|---|---|---|---|
| 16-42, 3.0, 0.23 | 4.1 | 0.99 | 0.17<br>(6) | 0.98 | 0.37 |
| 23-28, 3.0, 0.23 | 1.9 | 0.81 | 3.45‡<br>(6) | 0.98 | 0.16 |
| 25-38, 3.0, 0.23 | 4.0 | 1.04 | 0.62<br>(6) | 0.98 | 0.35 |
| 26-36, 0.3, 1.12 | 3.0 | 0.90 | 1.26<br>(4) | 0.98 | 0.34 |
| 25-36, 1.3, 0.23 | 6.2 | 1.02 | 0.84<br>(5) | 0.99 | 0.23 |
| 25-37, 0.3, 1.6 | 2.0 | 1.06 | 0.87<br>(3) | 0.99 | 0.18 |
| 32.2, 0.3, 0.23 | 4.4 | 1.10 | 1.26<br>(4) | 0.98 | 0.43 |
| 20-31, 0.5, 0.23 | 7.5 | 0.99 | 0.71<br>(7) | 0.99 | 0.22 |
| 32.2, 0.3, 0.23 | 6.9 | 0.91 | 1.39<br>(5) | 0.98 | 0.68 |
| 24-32, 3.0, 0.47 | 3.4 | 0.99 | 0.01<br>(6) | 0.93 | 0.64 |

*Goodness-of-fit was evaluated by checking the linear regression between observed and predicted hypocotyl lengths.

†From left to right the numbers represent soil temperature range in C, moisture in bars, and physical impedance in kg/cm².

‡Indicates a significant difference between the coefficient and 1.0 at the 0.05 level. Numbers in parentheses are degrees of freedom.

physical impedance were measured every other day. These environmental data were used as inputs for the simulations of the emergence tests.

In general, the model did an adequate job of simulating cotton emergence when soil inputs were properly measured. An example of results obtained where the soil environment was favorable is shown in Fig. 2.

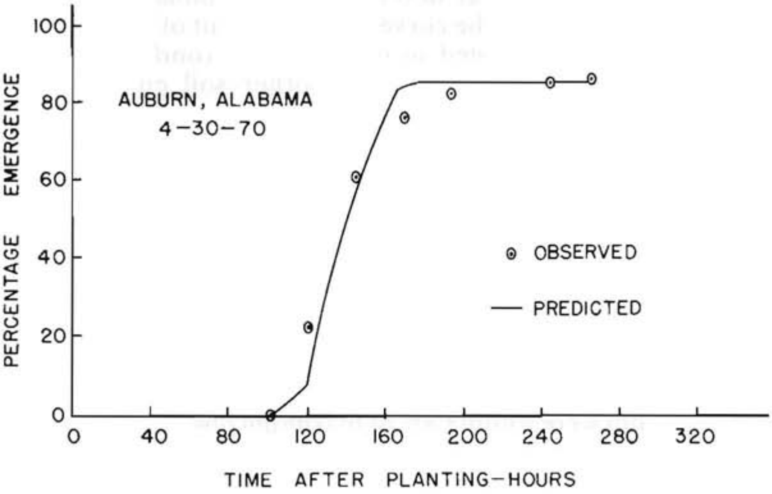

**Figure 2.—Example of emergence simulation results for a favorable soil environment.**

## Model Applications

The usefulness of a model lies in its use in simulation. In simulation the model is operated under varying levels of one or more factors (inputs) affecting the response (output). Two example applications of simulation use of the emergence model are discussed below.

*Sensitivity Analysis*

One type of simulation involves holding all inputs except one at constant levels that do not limit the output. The model is then repeatedly operated and the level of one input is changed for each operation. This procedure shows the effect of varying levels of a single input and is often referred to as "sensitivity analysis." Sensitivity analysis was used to study the effect of soil temperature, soil moisture tension, soil physical impedance, and planting depth on cotton emergence and is discussed elsewhere (2).

*Estimating Percentage Emergence*

The ability to predict emergence for different weather regimes is another potential application of the model and can be a useful tool for producers and researchers interested in developing improved techniques or equipment for planting and stand establishment. The basic relationship in the predictive method is the dimensionless ratio (EP/GP): emergence percentage divided by germination percentage plotted against planting depth as shown by the solid-line curve in Fig. 3. This relationship was developed from simulations with the cotton emergence model. The curve is independent of seed germination percentage and is limited to optimum soil conditions. Similar relationships could be developed for other soil environmental conditions.

One needs to know the planting depth and standard-test seed germination percentage to use Fig. 3. For example, if planting depth is 3.8 cm, the ratio taken from the curve is 0.93. By multiplying standard-test seed germination percentage by 0.93 one could estimate the maximum emergence percentage for optimum conditions. The validity of the solid-line curve shown in Fig. 3 was tested with field emergence data (Table 3). The predicted results compare very favorably with field observations, with the exceptions of those at Clemson, S.C., and Lubbock, Tx. in 1970 which had unusually high emergence. Other predictions were within ± 8% of maximum observed emergence.

A producer could use Fig. 3 to estimate how much seed to plant. For example, late in the planting season he might expect conditions to be near optimum and could anticipate emergence close to that indicated by the solid-line curve in Fig. 3. Early in the season he could expect emergence to be lower. The dotted-line curves are unverified model estimates for less favorable temperatures.

For the individual involved in develping planting equipment, Fig. 3 can serve to estimate how close emergence from a particular planting test comes to the theoretical maximum. This information, along with a record of soil temperature, soil moisture, and physical impedance, would suggest whether reduced emergence was caused by unfavorable physical soil conditions. A knowledge of weather conditions will then make it possible to attribute unfavorable soil environment to above-ground environment or perhaps to the planting equipment or planting technique used.

The approach discussed here led to the development of a cotton seedling emergence model. Used as a predictor, the model estimates expected seedling emergence for different kinds of environments. As a simulator (to estimate what would happen for assumed situations) the model can stimulate thinking and lead to new knowledge and insight of the emergence system.

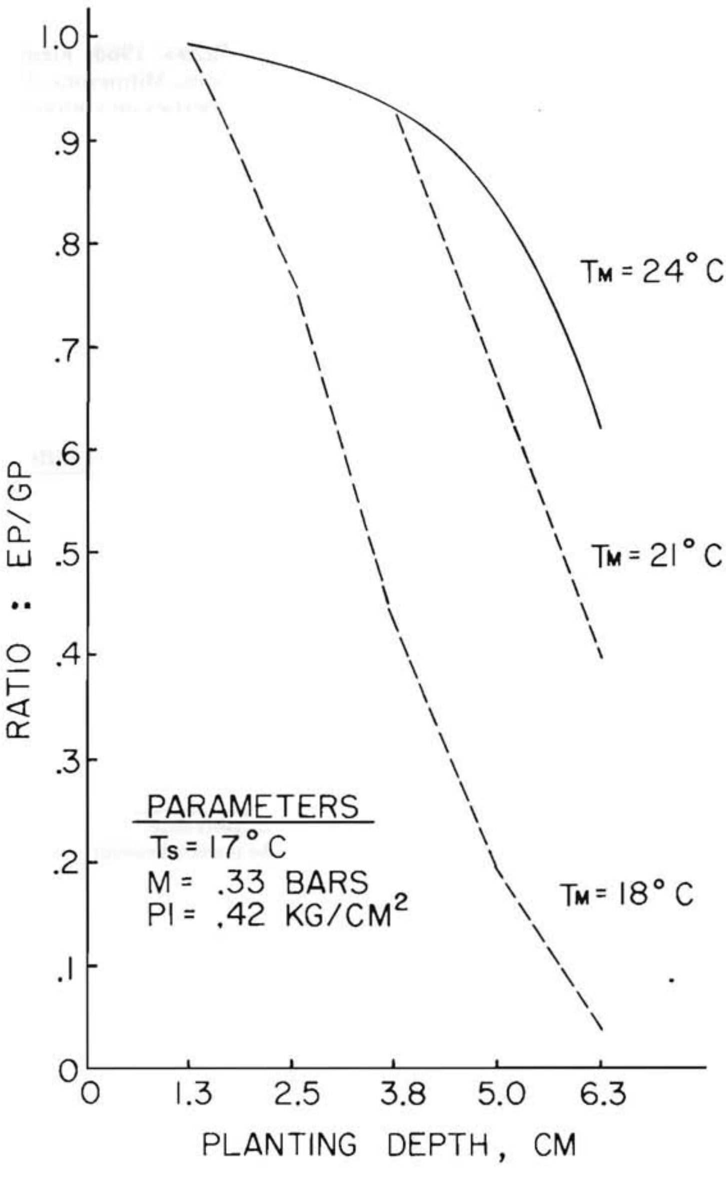

**Figure 3.—Graphical procedure for estimating maximum expected emergence percentage. At seed level, $T_m$ is the daily mean temperature, $T_s$ is the total daily temperature fluctuation, and M is soil moisture tension. PI is the physical impedance of the soil above the seed.**

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**Table 3. — Comparison of Field Emergence and Predicted Emergence, From the EP/GP-Depth Curve (Fig. 3) for Optimum Soil Environmental Conditions.**

| Location | Planting depth | EP/GP* | Maximum emergence Observed | Predicted | Difference** |
|---|---|---|---|---|---|
| | cm | | Percent | Percent | Percent |
| 1970 | | | | | |
| Clemson, SC | 3.2 | 0.95 | 99.7 | 82.7 | 20.6 |
| Chickasha, OK | 3.8 | 0.93 | 81.3 | 86.5 | −6.0 |
| Auburn, AL | 2.6 | 0.97 | 86.3 | 85.4 | 1.1 |
| Lubbock, TX | 5.0 | 0.84 | 100.0 | 78.1 | 28.0 |
| 1971 | | | | | |
| Baton Rouge, LA | 2.5 | 0.97 | 91.7 | 87.0 | 5.4 |
| DO | 2.8 | 0.96 | 92.6 | 86.0 | 7.7 |
| St. Joseph, LA | 5.0 | 0.84 | 77.8 | 75.6 | 2.9 |
| State College, MS | 3.8 | 0.93 | 75.5 | 81.0 | −6.8 |
| Lubbock, TX | 5.0 | 0.84 | 80.8 | 75.0 | 7.7 |
| Auburn, AL | 3.0 | 0.95 | 96.5 | 89.3 | 8.1 |

*Emergence percentage divided by standard germination percentage.

**Observed emergence minus predicted emergence divided by predicted emergence: (O-P)/P.