

Modeling Sorghum Seedling Establishment from Soil Wetness and Temperature of Drying Seed Zones

G. S. Brar,* J. L. Steiner, P. W. Unger, and S. S. Prihar

ABSTRACT

Existing crop simulation models predict emergence based on experimental results on the effects of soil temperature and water in systems sealed against evaporation. Under field conditions, however, the seed zone is open to evaporation. Seed zone water decreases with time and is often inversely related to soil temperature. Little is known about the combined effects of soil temperature and water on sorghum [*Sorghum bicolor* (L.) Moench] emergence rates in drying seed zones. Therefore, our objective was to study this and to model the effect to predict seedling stand establishment. Greenhouse experiments were conducted to study sorghum emergence at six constant temperatures (8.8, 15.9, 20.5, 25.2, 30.2, and 35.8 °C) attained on a thermogradient plate, and three initial soil water matric potentials (ψ_s) (-0.03, -0.1, and -0.3 MPa), using a Pullman clay loam. Emergence and plant height were recorded daily for 2 wk and root length was measured at termination of the experiment. We developed a sorghum stand establishment model that utilizes heat units and indices of emergence or growth as input parameters to predict emergence and root and shoot growth of seedlings. Optimum sorghum emergence (>80%) was obtained at temperatures of 20.5 to 30.2 °C, and -0.03 to -0.1 MPa ψ_s . Furthermore, combinations of cool temperature (15.9 °C) and ψ_s of -0.1 MPa as well as warm temperature (35.8 °C) and ψ_s of -0.03 MPa produced satisfactory emergence (>80%). Sorghum emergence regressed with thermal emergence index yielded a highly significant ($P < 0.0001$) positive nonlinear correlation (Adj. $R^2 = 0.62$). Similarly, main axis root length, lateral root length, and plant height regressed with thermal indices of main axis root length, lateral root length, and shoot growth yielded significant ($P < 0.0001$) positive, nonlinear correlations (Adj. $R^2 = 0.46, 0.70, \text{ and } 0.77$, respectively). The model should provide more realistic sorghum emergence predictions than models developed in systems closed to evaporation.

AN IMPORTANT STEP in growing a successful sorghum crop is obtaining an adequate plant population. Sorghum stand establishment can be adversely affected by soil water deficiency, extreme fluctuations of soil temperature, unfavorable soil physical and chemical properties, poor seed vigor, accumulation of residual herbicide, etc. According to Radford et al. (1989), only 55% of sorghum seed planted in the field in Australia resulted in successful plant establishment. They estimated that sorghum growers were losing 30% of their potential yield primarily due to inadequate plant density.

Existing simulation models predict germination or seedling emergence based on the effect of temperature and seed-zone water content on seed water absorption determined in systems sealed against evaporation (Fayemi, 1957; McGinnies, 1960; Chaudhary et al., 1971; Woods and McDonald, 1971; Wanjura and Buxton, 1972; Lindstorm et al., 1976; Sharma, 1976; Romo and Haferkamp, 1987; Webb et al., 1987). In such systems, the water imbibition by seeds, germi-

nation rate, and final germination of crops have been reported to be linearly affected by temperature (Burch and Delouche, 1959; Dewez, 1964; Hegarty, 1973; Bierhuizen and Wagenvoort, 1974; Thompson and Fox, 1976; Heydecker, 1977). In actual field situations, however, the seed zone is open to evaporation and seed zone water content decreases with time. In this regard, temperature interacts with water. The development rate of the crop is determined by a dynamic environment around the seed in which temperature, adsorption, and evaporation are interactive and where high temperatures tend to decrease water absorption and reduce emergence.

Gill and Prihar (1988) studied the seedling emergence of barley (*Hordeum vulgare* L.) as affected by soil temperature and water content in drying seed zones. Their results differed from previous observations in that emergence at higher temperature declined in the drying seed zones while it should have increased according to the existing information. Similar observations for sorghum are not available, and no effort has been made to model soil temperature and soil water effects on sorghum seedling emergence, as well as root and shoot development in drying seed zones. We studied and modeled these effects in greenhouse experiments with a system open to evaporation. Therefore, our objectives were to (i) study the effect of seed zone temperature on sorghum emergence and root and shoot growth, (ii) evaluate the impact of a drying seed zone on seedling establishment, (iii) determine soil temperature-water content combinations for optimum seedling emergence, and (iv) develop a simple model to predict sorghum seedling stand establishment.

MATERIALS AND METHODS

Greenhouse experiments were conducted at the USDA-ARS Conservation and Production Research Laboratory, Bushland, TX, using a Pullman clay loam (fine, mixed, thermic Torric Paleustoll) collected from the 0- to 15-cm surface layer. The soil was dried and passed through a 2-mm mesh screen. Water retained at -0.03, -0.1, and -0.3 MPa matric potentials on a pressure plate was 0.237, 0.173, and 0.154 kg kg⁻¹ at a bulk density of 1.33 Mg m⁻³, respectively. The processed soil was packed in aluminum micro lysimeters (40 mm wide, 100 mm long, and 140 mm deep) to obtain a uniform bulk density of 1.33 Mg m⁻³. The micro lysimeters were placed inside a thermogradient plate device (1.2 m long, 0.75 m wide, and 0.20 m deep) in five rows of six lysimeters per row. Coarse sand was used as a medium for heat transfer as well as to fill the voids among the lysimeters and thermogradient plate. The constant soil temperature regimes (8.8, 15.9, 20.5, 25.2, 30.2, and 35.8 °C) were obtained by cooling one end and heating the other with circulating water baths. Heat loss was controlled with 25 mm thick insulation on the sides and base of the thermogradient plate device. The top of the device was tightly covered with a 25 mm thick polystyrene sheet with openings cut to leave the soil in the lysimeters open to evaporation. A measured amount of deionized water equivalent to -0.03, -0.1, and -0.3 MPa soil matric water potential (ψ_s) was added to each lysimeter. The lysimeters were sealed with plastic covers for 48 h to allow

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water redistribution as well as temperature equilibrium with the sand.

The sorghum cultivar 'Richardson-9112' used for this study was selected from 13 cultivars tested for germination at different temperatures because of faster and superior performance. Individual seeds were examined and cracked seeds were discarded. Individual seeds were examined and cracked seeds were discarded. Plastic covers were removed from the lysimeters and soil gravimetric water content was recorded at the time of hand planting five uniform seeds at the 50-mm depth. Additional water content determinations were made three times weekly for 2 wk. Hourly mean temperatures at the 50-mm depth were measured using copper-constantan thermocouples logged with a data logger, Model CR-7 (Campbell Scientific, Inc., Logan, Utah)¹. Daily means of hourly temperature were used to accumulate heat units for each micro lysimeter.

Base temperature (Fig. 1) corresponds to zero development rate and was determined following the linear regression method of Kanemasu et al. (1975). Their model can be written as:

$$T = b_0 + b_1 * t^{-1} \quad [1]$$

where T = seed zone temperature, (°C); b_0 = base temperature (°C); b_1 = slope of the curve; t = time to complete 50% emergence (d). Accumulated heat units (HU, °C d) were computed from Eq. [2] as reported by Singh et al. (1984):

$$HU = \sum_{i=1}^n (T_i - b_0) \quad [2]$$

where T_i = average daily seed zone temperature (°C) on day of observation, and n = total number of days for final sorghum emergence or growth. Emergence index (I_e , %/d) of five planted seeds was calculated by using the following formula:

$$I_e = \sum_{i=1}^n ei/di \quad [3]$$

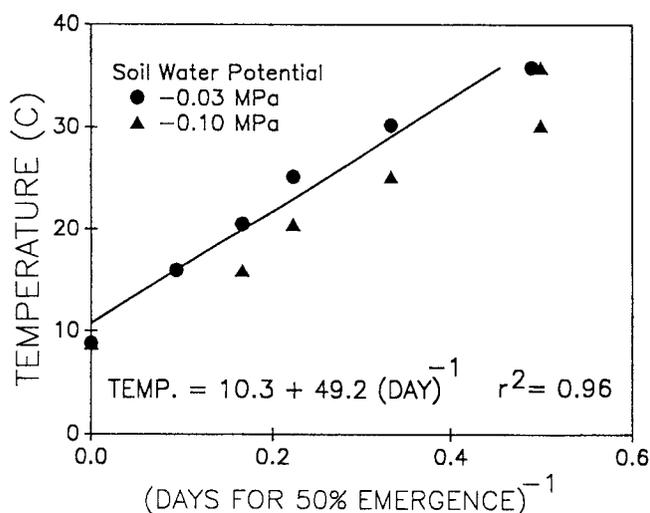


Fig. 1. Base temperature for sorghum emergence from constant seed zone temperature data.

¹ Mention of a company name or trademark is for the reader's benefit and does not constitute endorsement of a particular product over others that may be commercially available.

where ei = cumulative number of seedlings emerged on day i , and di = number of days from planting to day i . The thermal emergence index (I_{et} , °C %) was the product of HU times I_e .

The main axis root length (MARL) or lateral root length (LRL) indices (I_m or I_l , mm/d) were estimated from the ratio of the total root length at harvest to total time (days after planting to harvest) for each temperature and water content treatment. The MARL or LRL thermal indices (I_{mt} or I_{lt} , °C mm) were the products of HU time I_m or I_l , respectively. The shoot index (I_s , mm/d) for each temperature and water content treatment was calculated from the following formula:

$$I_s = \sum_{i=1}^n \text{phi}/di \quad [4]$$

where phi = plant height (mm) at day i .

Soil heat units (HU_s) were calculated from Eq. [2] and aerial heat units (HU_a) were estimated by the summation of the difference of daily average greenhouse temperature and base temperature. The total heat units (HU_t) for shoot growth were determined by averaging HU_s and HU_a . The thermal shoot index (I_{st} , mm/d) was the product of HU_t times I_s .

The experimental design was considered as a series of experiments repeated over soil ψ_s and fixed temperatures were applied within each ψ_s . Temperature treatments were replicated non-randomly three times perpendicular to the temperature gradient. Each ψ_s experiment was repeated three times. The analysis of variance was structured according to Kempthorne (1952), and the design allows only the testing of temperature main effects. Multiple regression analyses were performed (PROC REG, method = cp, SAS, 1990) where the dependent variables were emergence time (t , d), emergence index (I_e , %/d), final emergence (e , %), main axis root length (MARL, mm) index (I_m), lateral root length (LRL, mm) index (I_l), shoot index (I_s), and plant height (P_h , mm), and independent variables were seed zone temperature (T), ψ_s , thermal indices of emergence (I_{et} , °C %), MARL (I_{mt} , °C mm), LRL (I_{lt} , °C mm), and shoot (I_{st} , °C mm).

RESULTS AND DISCUSSION

Effect of Temperature and Water Content on Seedling Establishment

Emergence was poor at -0.3 MPa at all temperatures, and data for this treatment were excluded from the discussion. Sorghum final emergence at -0.03 MPa ψ_s increased with increased temperature from 15.9 to 25.2 °C and declined when temperature exceeded 25.2 °C (Fig. 2). Low emergence (66.7%) was recorded at the combination of low temperature (15.9 °C) and high ψ_s (-0.03 MPa), which may be attributed to reduced oxygen diffusion due to a thick water film around the seed (Dasberg and Mendel, 1971) and to low temperature, which limits seedling development prior to emergence by reducing initiation of cell division, water absorption, and synthesis of organic compounds (Trowse, 1971). The reduction in seedling emergence to 53.3% at low ψ_s (-0.1 MPa) and high soil temperature (35.8 °C) apparently resulted from increased soil strength, and possibly due to low seed-soil water contact. Maximum emergence (100%) at 25.2 °C was unaffected by change in ψ_s . At 8.8 °C, seeds germinated but no emergence occurred. Seeds can germinate but not emerge because of pathogens and loss of seed reserves (Angus et al.,

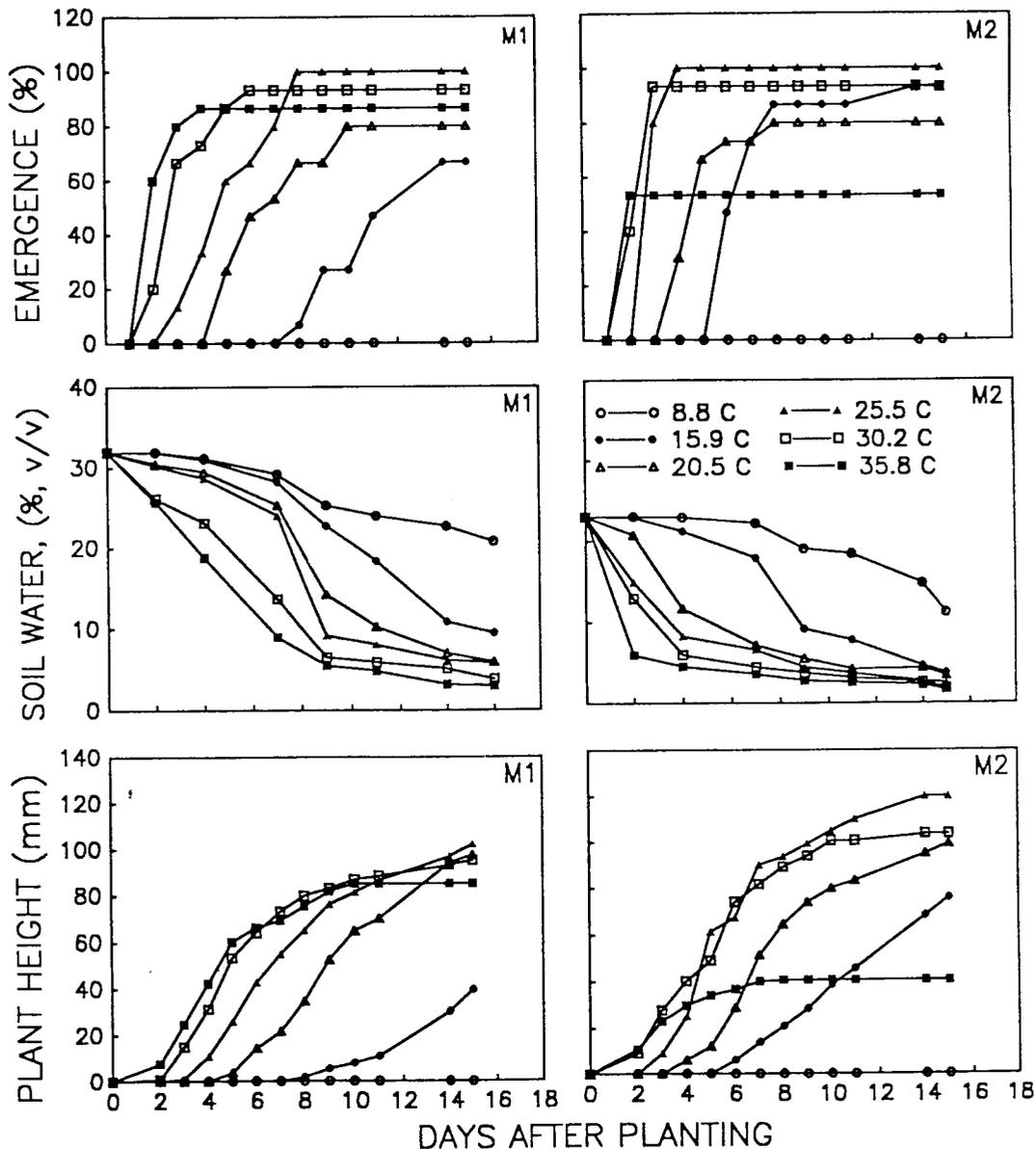


Fig. 2. Sorghum emergence, soil water content, and plant height as influenced by time after planting at $M_1 = -0.03$ and $M_2 = -0.1$ MPa soil water potential

1981). Differences in soil water matric potential at temperatures of 20.5, 25.5, and 30.2 °C had no effect on final emergence.

Water loss was faster at warmer than at cooler temperatures (Fig. 2). Cumulative emergence counts increased as long as the seed zone water content was above threshold (11.4% vol/vol at -1.5 MPa) level and ceased thereafter (Fig. 2). The general effect of decreasing ψ_s is to retard the seed imbibition rates and to delay germination and emergence (Collis-George and Sands, 1959). However, if ψ_s is sufficiently high to allow germination, then postgermination growth and emergence is quite possible (Collis-George, 1987).

Two weeks after planting, the order of the plant height of the temperature treatments was 25.2 > 20.5 > 30.2 > 35.8 > 15.9 > 8.8 at -0.03 and 25.2 > 30.2 > 20.5 > 15.9 > 35.8 > 8.8 °C at -0.1 MPa ψ_s (Fig. 2). Seedlings, except at the extreme temper-

atures, were taller when grown at -0.1 than at -0.03 MPa ψ_s . This can be attributed to greater root development at -0.1 MPa ψ_s (Table 1). Main axis root length and LRL increased with increases in temperature from 15.9 to 30.2 °C and decreased at 35.8 °C. In semiarid environments, rapid germination permits the secondary root system to access wet soil ahead of the drying front (McCown et al., 1985).

The root-shoot ratio of sorghum seedlings was affected by temperature as well as soil water potential (Table 2). The ratio significantly increased with increases in temperature from 15.9 to 25.2 °C and declined at temperatures of 30.2 and 35.8 °C. Furthermore, the ratio was greater with -0.10 than -0.03 MPa ψ_s at 15.9, 20.5, and 30.2 °C temperature. Gonzalez and Jordan (1990) reported higher root-shoot ratio of stressed sorghum plants relative to controls.

Table 1. Main axis root length (MARL) and lateral root length (LRL) of sorghum seedlings at 2 wk as affected by soil temperature and soil water potential. Data are means of three observations.

Soil temperature °C	MARL		LRL	
	Soil Water Potential, MPa			
	-0.03	-0.10	-0.03	-0.10
	mm			
15.9	70.7 ^{a†}	79.3 ^{bc}	60.3 ^b	134.9 ^b
20.5	80.0 ^a	97.5 ^{abc}	375.7 ^a	459.6 ^a
25.2	82.7 ^a	99.3 ^{ab}	486.4 ^a	546.5 ^a
30.2	83.3 ^a	141.0 ^a	447.0 ^a	580.3 ^a
35.8	86.0 ^a	50.8 ^c	372.2 ^a	103.9 ^b
LSD ($P \leq 0.05$)	23.6	48.5	184.1	203.0

† Within columns, means not followed by a common letter differ ($P \leq 0.05$) according to Fisher's Least Significant Difference Test.

Table 2. Root-shoot ratio of sorghum seedlings as affected by soil temperature and soil water matric potential. Data are means of three observations.

Soil temperature °C	Root-shoot ratio	
	Soil water potential, MPa	
	-0.03	-0.10
15.9	0.34 ^{b†}	0.43 ^{ab}
20.5	0.39 ^b	0.60 ^a
25.2	0.75 ^a	0.66 ^a
30.2	0.39 ^b	0.44 ^{ab}
35.8	0.36 ^b	0.06 ^b
LSD ($P \leq 0.05$)	0.35	0.42

† Within columns, means not followed by a common letter differ ($P \leq 0.05$) according to Fisher's Least Significant Difference Test.

Seedling Establishment Model

The three major components of the sorghum seedling establishment model include: (i) Predicting sorghum emergence; (ii) Predicting root growth; and (iii) Predicting plant height.

Emergence Model

A significant ($P < 0.0001$) relationship was observed for time taken to reach maximum emergence with root zone temperature and ψ_s (data not shown). The emergence time (t) regressed with seed zone temperature (T) and ψ_s explained 80% of the variation in observed emergence time as a function of drying seed zone temperatures and ψ_s (Table 3). Similarly, significant ($P < 0.0001$) positive correlations for emergence index (I_e , %/d) with seed zone temperature (T) and ψ_s (Table 3) were discovered. The regression for emergence index with seed zone temperature (T) and ψ_s explained 89% of the variation in I_e .

Highly significant ($P < 0.0001$) positive nonlinear correlation between final emergence (e) and thermal emergence index (I_{et}) was noticed (Fig. 3) which accounted for 62% of observed variation.

Root Growth Model

The indices, MARL (I_m , mm/d) and LRL (I_l , mm/d) were positively correlated with seed zone temperatures and ψ_s and explained approximately 40% of observed variation (Table 3).

Table 3. Regressions for growth and emergence indices of sorghum as a function of seed zone temperature (T) and soil water matric potential (ψ_s). $Y = \beta_0 + \beta_1 T + \beta_2 \psi_s$, $n = 30$.

Variable	Equation	β_0	β_1	β_2	$R^2 \dagger$
Emergence time (t)	$= 21.18^{***} - 0.51T^{***} + 20.95\psi_s^*$	(1.39) [‡]	(0.05)	(9.44)	0.80
Emergence index (I_e)	$= -0.19^{***} + 0.01T^{***} - 0.82\psi_s^{***}$	(0.03)	(0.00)	(0.18)	0.89
MARL index (I_m)	$= -0.07 + 0.02T^{***} - 0.77\psi_s$	(0.11)	(0.003)	(1.05)	0.41
LRL index (I_l)	$= -0.54 + 0.11T^* - 1.30\psi_s$	(0.60)	(0.02)	(5.70)	0.39
Shoot growth index (I_s)	$= -0.68^{**} + 0.08T^{***} - 1.72\psi_s$	(0.21)	(0.01)	(1.98)	0.74

***, ** Significant at $P \leq 0.05$, 0.01, and 0.001, respectively.

† Coefficient of determination.

‡ Figures in parentheses denote the standard error of the coefficient.

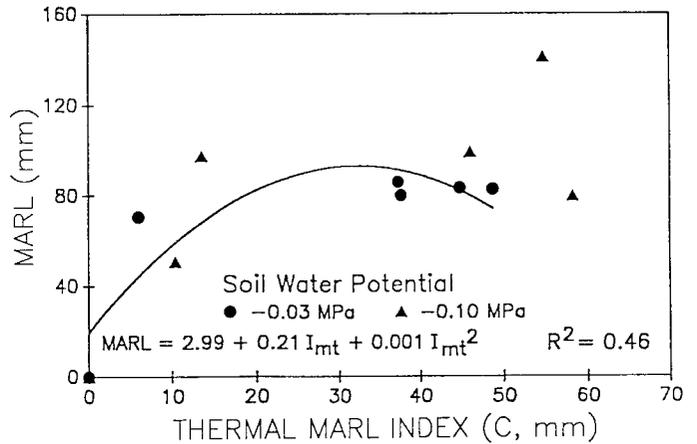


Fig. 3. Curvilinear relation of sorghum emergence (e) at -0.03 and -0.1 MPa soil water potentials with thermal emergence index (I_{et}).

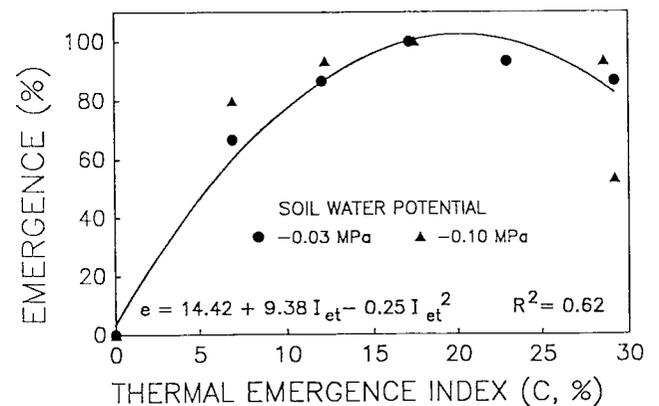


Fig. 4. Curvilinear relation of main axis root length (MARL) at -0.03 and -0.1 MPa soil water potentials with thermal MARL index (I_m).

We found significant ($P < 0.0001$) positive correlations between MARL or LRL as a dependent variable with thermal MARL index (I_{mt}) or thermal LRL index (I_{lt}) as an independent variable (Fig. 4 and 5). Furthermore, I_{mt} or I_{lt} accounted for 46 and 70% of ob-

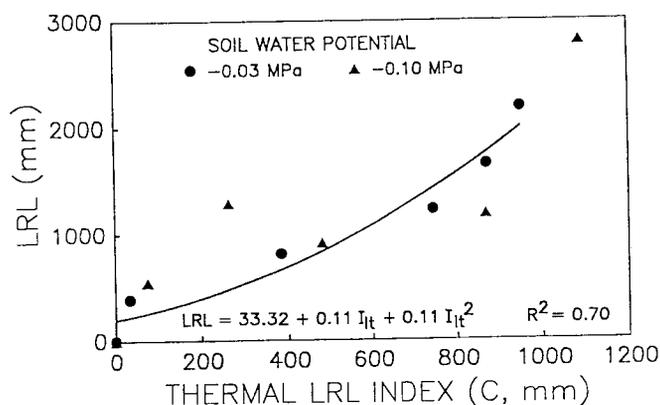


Fig. 5. Curvilinear relation of lateral root length (LRL) at -0.03 and -0.1 MPa soil water potentials with thermal LRL index (I_{lt}).

served variation in MARL or LRL, respectively. Additionally, I_{lt} was 20 times greater than I_{mt} .

Shoot Growth Model

The shoot index (I_s , mm/d) was positively correlated with soil temperatures and ψ_s (Table 3). The model accounted for 74% of observed variation in I_s .

A highly significant ($P < 0.0001$) positive nonlinear correlation between the dependent variable, plant height (p_h) and the independent variable, I_{st} (Fig. 6) was found. The model accounted for 77% of the observed variation in plant height.

In this experiment, the seedling emergence time (t) and growth indices (I_e , I_m , I_l , and I_s) were more sensitive to temperature than soil water potential (even though the coefficients for T in Table 3 appear small, the magnitude of the T variable is much larger than the ψ_s variable). The sensitivity of the growth indices to T was $I_e < I_m < I_s < I_l$. For ψ_s , sensitivity of the indices was $I_m < I_e < I_l < I_s$. Emergence and root elongation (I_e and I_m) occur under a relatively wide range of T and ψ_s conditions, but for rapid shoot growth and lateral root development (I_s and I_l), favorable T and ψ_s conditions are required. The conditions of the experiment did not allow establishment of a gradient of soil water potentials, rather just a few fixed points.

CONCLUSIONS

The combination of a cool temperature (15.9°C) and moderate level of stored water (-0.1 MPa) at planting produced satisfactory emergence counts (80%), which indicates that early planting might be possible for dryland sorghum production. Similarly, a combination of warm temperature (35.8°C) with high stored water (-0.03 MPa) provided a favorable environment for 87% seedling emergence. This study indicated that at temperatures of 20.5 to 30.2°C , stored water at planting between -0.03 and -0.1 MPa ψ_s had no effect on final emergence. Seedling root development was greater at -0.10 than at -0.03 MPa ψ_s which might be advantageous for early establishment of sorghum planted under dryland or limited water conditions. The simple sorghum seedling establishment model based on heat units and emergence or growth

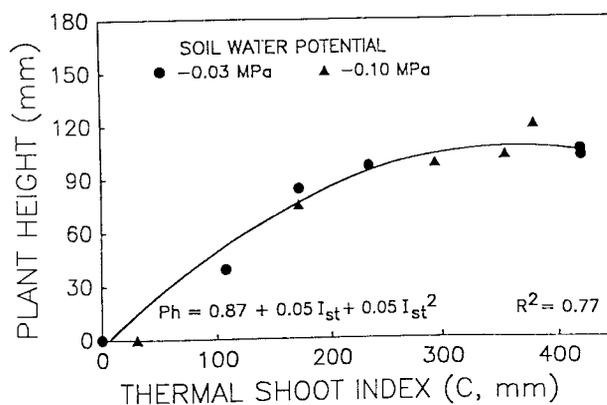


Fig. 6. Curvilinear relation of plant height (Ph) at -0.03 and -0.1 MPa soil water potentials with thermal shoot index (I_{st}).

indices accounted for 62, 46, 70, and 77% of the variation in final emergence, main axis root length, lateral root length, and plant height, respectively, under different temperature and soil water regimes. The model has superiority over the previous models which were developed in systems closed to evaporation. However, it would be highly desirable to identify a model form which allows mechanistic interpretation with a physiological basis for the coefficients, rather than the empirical quadratic form, which fit the data. Additional work is needed to identify a model which could be applied over a range of ψ_s , rather than only at set ψ_s . Many management practices, such as selection of planting date, type and dates of tillage, and surface residue management, affect seed zone water content and temperature. Improved understanding of temperature and water dynamics and interactive impacts of these factors on plant establishment, may lead to improved early season conditions for sorghum.

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