Predicting Seedling Emergence Using Soil Moisture and Temperature Sensors

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Abstract: Hydrothermal time models are often used to predict seed germination rates. In this study, soil water potential data from three resistance-type sensors (Colman cells, Watermark brand sensors, and Delmhorst gypsum blocks) and from a time-domain reflectometry (TDR) probe (Campbell Scientific 615) were input into a hydrothermal time model to predict seedling emergence in a growth chamber experiment for six desert grass species, including *Brachypodium distachyon, Bromus fasciculatus, Crithopsis delilianus,* and *Stipa capensis* from the Negev Desert, and naturalized downy brome (*Bromus tectorum*) and bottlebrush squirreltail (*Elymus elymoides*) from the Great Basin Desert. Seeds were sown in a structureless sandy loam soil that was irrigated approximating 0.58, 1.25, 1.50, and 2.00 times field capacity volumetric water content and allowed to dry in a growth chamber programmed to simulate spring temperatures in Provo, UT. Colman cells and Delmhorst gypsum blocks indicated more rapid soil surface drying than did Watermark sensors and TDR probes. Inputs provided by the sensors correctly predicted seedling emergence of these rapidly germinating grasses when water potential was high, but incorrectly predicted emergence when rapidly decreasing water potentials inhibited emergence. These results suggest that more accurate measurement or prediction of seed zone water potentials may be necessary before hydrothermal time models can effectively predict seedling emergence in the field.

Introduction

Annual and perennial grasses influence arid land plant communities by affecting biomass production, soil erosion, plant and herbivore interactions, and fire frequency. In the Negev Desert, Israel, annual grasses (such as *Brachypodium distachyon, Bromus fasciculatus, Crithopsis delilianus,* and *Stipa capensis*) provide important forage for grazing animals. In the Great Basin Desert, United States of America, introduced downy brome (*Bromus tectorum*) can invade and disrupt native perennial communities (Billings 1994; D'Antonio and Vitousek 1992).

Successful germination and seedling establishment in desert ecosystems is often limited by species-specific seed germination responses to near-surface soil water potentials and temperatures. Frasier (1987) reported that seedling survival for five warm-season desert grasses depended upon the number of seedlings that successfully emerged after initial wetting, the number of nongerminated and viable seed that remain, and the time interval between wet and dry periods. For example, the ability of Lehmann lovegrass (*Eragrostis lehmanniana*) to retain a viable seedbank during erratic summer rainfall in the Sonoran Desert grassland allows it to establish better than some native grasses that germinate most of their seeds after initial rains and are then subject to seedling desiccation (Abbott and Roundy 2003).

Seed germination models using soil matric potential (Ψ) and temperature data can be used to accurately predict germination (Allen and others 1999; Bradford 1990; Finch-Savage and Phelps 1993; Roman and others 1999). Gummerson (1986) was the first to combine water potential and temperature data to model germination (hydrothermal time). Hydrothermal time has since been used to successfully model germination for a variety of species (Allen and others 1999; Christensen and others 1997; Finch-Savage and Phelps 1993; Roman and others 1999).

Electric resistance sensors and time-domain reflectometry (TDR) probes are used to estimate soil moisture conditions (Amer and others 1994; Baker and Allmaras 1990; Collins 1987; Roundy and others 1997, 2001). Various sensors have been compared to see how they respond to changes in soil moisture. Topp and Davis (1985) compared TDR and gravimetric sampling at various depths within the top meter of soil and found both techniques produced similar results. Collins (1987) compared gypsum blocks with Colman cells and found that Colman cells had poor sensitivity in dry soils as well as large differences among individual sensor resistances. When comparing gypsum blocks and Watermark sensors, Hanson and others (2000) reported that gypsum blocks did not indicate reductions in soil water matric potential until the surrounding media fell below a certain moisture threshold. In addition, they found that Watermark

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sensors were more responsive in drier soils. In a comparison between Colman cells, TDR, and gravimetric sampling, Amer and others (1994) found that Colman cells tended to indicate higher soil moisture content and exhibited more variation, but were more effective at measuring shallow depths because they measure moisture at points. A more thorough and simultaneous comparison among available sensors in soils with widely fluctuating soil water potentials would better determine their ability to provide meaningful data to predict seedling emergence.

Hydrothermal Time

Nondormant seeds germinate after being exposed to suitable temperatures and water potentials for an adequate period of time (Allen and others 1999; Bradford 1995; Finch-Savage and Phelps 1993; Gummerson 1986; Roman and others 1999). Hydrothermal time can be described by the equation (Gummerson 1986):

$$HT = (\Psi - \Psi_{b(g)})(T - T_b)t_{(g)}$$

At the time of germination:

$$\theta_{HT} = (\Psi - \Psi_{b(g)})(T - T_b)t_{(g)}$$

HT is the amount of hydrothermal time that has accumulated (expressed as MPa-°-hours or days). The amount of hydrothermal time required for germination is θ_{HT} (the amount of HT that satisfies the requirement for radicle emergence). Ψ is the water potential of the soil, and $\Psi_{b(g)}$ is the minimum or base water potential for (g) fraction of the seeds to germinate for a given population. T is the temperature of the soil, and T_b is the minimum seed germination temperature. The time required for g fraction of the seeds to germinate is $t_{(g)}$.

Hydrothermal time analysis requires that data be probit transformed (to linearize the typical cumulative time course for germination of a particular collection). Transformed data are used to compare germination time differences among the various fractions of the seed population. Base soil water matric potentials (Ψ_b) are assumed to vary normally within the population. The $\Psi_{b(g)}$ of a given germination fraction from a population of seeds with a known $\Psi_{b(50)}$ can be calculated using a formula:

$$\Psi_{b(g)} = \Psi_{b(50)} + (\sigma_{\Psi b} \times prob_{(g)})$$

where $\Psi_{b(g)}$ is the minimum or base water potential for g fraction of the seeds to germinate from a given population, $\sigma_{\Psi b}$ is the standard deviation of the base water potential, and $prob_{(g)}$ is the probit conversion of fraction g. Although the model can algebraically calculate $\Psi_{b(g)}$ for any fraction, fractions beyond 2 standard deviations of the mean are less likely to be normally distributed.

Thermal Time

We adapted the thermal time (TT) equation from the hydrothermal time (HT) equation. In seed germination studies, TT describes the influence of temperature on seed germination rates. It predicts that radicle emergence will occur more rapidly as germination temperature increases until a maximum temperature threshold is reached. Because thermal time assumes that matric potential has no effect (in other words, it has a value of 0):

$$TT = (0 - \Psi_{b(g)})(T - T_b)t_{(g)}$$

which can be simplified to:

$$TT = (-\Psi_{b(g)})(T - T_b)t_{(g)}$$

The TT equation and the HT equation incorporate the same parameters with the exception of soil water potential. This can be useful for germination modeling when there is abundant soil moisture but an accurate Ψ measurement is unavailable.

Methods

We had three objectives in this study. First, compare the drying response of four different soil moisture sensors near the soil surface with different irrigation treatments. The sensors we used were TDR probes (Campbell Scientific, Inc., Logan, UT), Watermark brand sensors (Irrometer Co., Inc., Riverside, CA), Delmhorst gypsum blocks (Delmhorst Instrument Co., Towaco, NJ), and Colman cells (Soiltest Inc., Lake Bluff, IL). Second, use soil moisture data from the different sensors as driving variables in a hydrothermal time model for 11 grass seed collections from the Negev Desert, Israel, and the Great Basin, United States of America. Third, compare predicted and observed emergence for these 11 grass seed collections.

Soil Moisture Release Curve

We used a structureless, nonsaline (electrical conductivity 0.4 mmhos cm^{-1}), sandy loam (74.8 percent sand, 15.2 percent silt, and 8.5 percent clay) for this experiment. Water content of six soil samples was measured at 0.01, 0.033, 0.1, 0.3, 0.7, and 1.5 MPa using pressure plate Soil Moisture Equipment Co. extractors. The relationship between volumetric water content and matric tension was modeled using log-linear regression (double-log) focusing on three data points in the crucial area:

$$\Psi = e^{-14.3195} / x^{4.74341}$$

where Ψ is soil water matric tension (MPa) and x is volumetric water content (fig. 1).

Sensors

We buried three resistance-type sensors and one TDR probe in plastic trays. Colman resistance cells were individually calibrated for drying soil water content (Roundy and others 1997) to reduce the effects of sensor variability, while standard calibration curves were used for Delmhorst gypsum blocks (CSI 1983), Watermark sensors (CSI 1996a), and TDR probes (CSI 1996b). Resistance cells or blocks were all 2 cm in height or diameter and were buried at a depth of 1 cm (zone of measurement 1 to 3 cm). The TDR probe had two 3.2 mm diameter rods 30 cm long and spaced 3.2 cm apart. Rods were buried at 3.5 cm with the effective measurement environment being 2.5 cm above and below the rods (zone of measurement = 0.5 to 5.5 cm). Soil temperatures were measured at the same depth as resistance sensors using

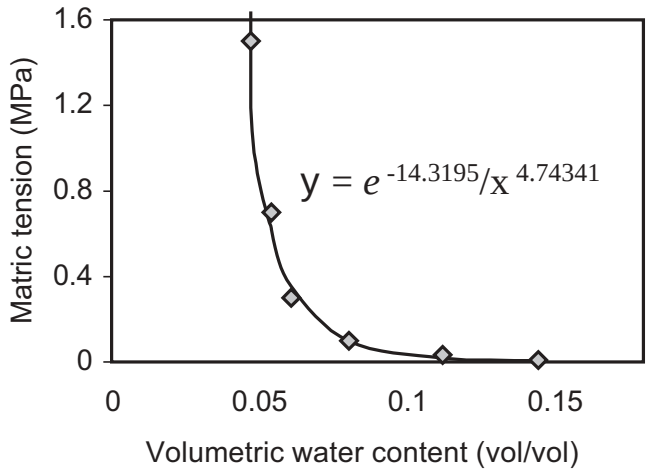

Figure 1—Moisture release curve for the sandy loam soil used in study. Data points indicate observed values; line is from equation.

thermocouples. Four resistance sensors of each type and one TDR probe were buried in each of eight trays (four blocks each receiving one of two irrigation treatments). Trays measured 60 cm long by 43 cm wide by 15 cm deep. We drilled holes in the bottoms of each tray to allow drainage. Sensors were read every minute with CR-10 microloggers (Campbell Scientific, Inc., Logan, UT), and hourly averages were recorded. We converted soil volumetric water content to soil water matric potential for the Colman cells and TDR probes using the moisture release curve (fig. 1).

Growth Chamber Experiment

Fifty seeds from 11 seed collections, including six species, were sown in each tray prior to irrigation. Collections came from the Negev Desert of Israel (*Brachypodium distachyon* [Brdi, 1996 and 1998], *Bromus fasciculatus* [Brfa, 1996 and 1998], *Crithopsis delilianus* [Crde, 1996 and 1998], and *Stipa capensis* [Stca 1997]) and the Great Basin of Utah (*Bromus tectorum* [Brte 15-Whiterocks, Utah, 1996, 1997–1999 Mix, Brte 18-Hobble Creek, Utah, 1996], and *Elymus elymoides* [Elel, 2000]). We sowed seeds of each collection at a depth of 3 to 5 mm with the exception of *Crithopsis delilianus*, which we sowed at a depth of 6 to 8 mm.

Trays were sequentially irrigated and allowed to dry on two occasions. Trays were initially assigned treatment one and two and received 1,363 and 2,934 mL of water, respectively (approximately 0.58 field capacity volumetric water content (fc) or 1.25 fc). Trays were later assigned treatments three or four and rewetted with 3,521 and 4,695 mL of water, respectively (approximately 1.50 fc or 2.00 fc). Trays were arranged in randomized blocks.

We counted seedlings daily and calculated emergence as a percentage of viable seeds. Seed viability for each collection was determined in preliminary germination tests with four replications. We placed 25 seeds from each collection in petri dishes lined with moist blotter paper. Dishes were then placed in incubation chambers programmed at 15, 20, and 25 °C. We considered a seed to have germinated when the radicle exceeded 2 mm. Time required for coleoptile emergence after germination was estimated by regressing the time required for coleoptiles to exceed 3 mm on the temperature of incubation (fig. 2). We estimated time for emergence after germination using the average thermocouple temperature reading within a tray during a corresponding irrigation and drying cycle.

Hydrothermal Time and Thermal Time Parameters

We assumed the hydrothermal time constant (θ_{HT}) and the base temperature (T_b) were constant for each nondormant seed collection (table 1). Hydrothermal parameters for fully after-ripened seeds of the collections were developed using repeated probit regression (Christensen and others 1996; Meyer and others 2000; Taylor and others, unpublished data on file).

Both the hydrothermal time and thermal time models used an average thermocouple temperature reading from four locations, each 3 cm deep, for each corresponding tray. Average soil water matric potential values for each resistance sensor type were calculated similarly while a single TDR probe provided soil water matric potentials for each tray.

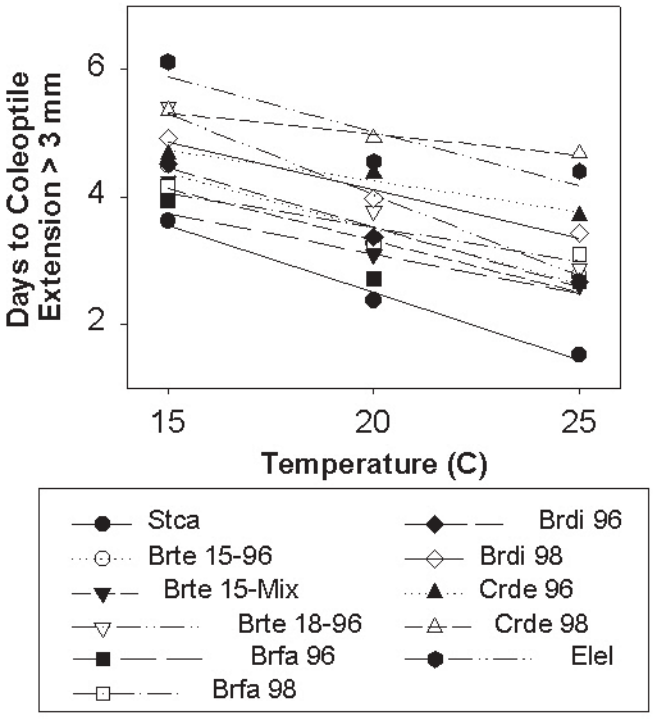

Figure 2—Days for coleoptile extension to more than 3 mm at different incubation temperatures. Coefficient of determination (r-squared) values ranged between 0.78 and 0.98.

Table1—Hydrothermal time parameters for each of the 11 seed collections[a].

Species	Year	θ_{HT} (MPa-°-hrs)	$\Psi_{b(50)}$ (MPa)	T_b (C)	$\sigma_{\Psi b}$ (MPa)
B. distachyon	1996	672	–0.85	2.2	0.328
B. distachyon	1998	864	–0.58	2	.372
B. fasciculatus	1996	744	–1.22	0.7	.326
B. fasciculatus	1998	480	–0.72	1	.315
B. tectorum-15	1996	744	–1.01	0	.337
B. tectorum-15	Mix[b]	744	–1.06	0	.337
B. tectorum-18	1998	672	–0.76	0	.377
C. delileanus	1996	1296	–1.08	4.4	.382
C. delileanus	1998	384	–0.57	10	.276
E. elymoides	2000	2500	–1.57	0	.277
S. capensis	1997	672	–1.23	0	.334

[a] From Taylor, Meyer, Allen, and Roundy, in preparation.
[b] Mix—includes seeds from 1997, 1998, and 1999.

Results and Discussion

All soil moisture sensors behaved consistently during the irrigation and drying cycles. Colman cells and gypsum blocks indicated more rapid drying than Watermark and TDR sensors (fig. 3). Colman cells responded to soil drying most rapidly. The drying pattern for gypsum blocks was similar to Colman cells, but readings usually lagged 1.5 to 2 days (fig. 3). Watermark sensors responded to the 0.58 fc and 1.25 fc treatments more slowly than the other sensors, but exhibited the least amount of variation between individual sensors within their limited range of sensitivity (0 to –0.2 MPa) (fig. 3). Compared with TDR, Colman cells measured soil moisture over a smaller soil volume. The depth interval of measurement of the TDR probes was 0.5 to 5.5 cm, making them the least sensitive to near-surface drying.

The hydrothermal time model and thermal time models generally predicted similar seedling emergence from water potential inputs or thermal inputs for each of the sensors, but usually predicted emergence sooner than actual emergence occurred (fig. 4). Slower actual than predicted emergence may be due to soil impedance of coleoptiles and by lower soil matric potentials in the seed zone than where the sensors were buried. The latter explanation is supported by the results from drier irrigation treatments (fig. 4—fc x 0.58, fc x 1.25, and fc x 1.50). In three of the irrigation treatments (0.58, 1.25, and 1.5 fc), both the hydrothermal time model and thermal time models incorrectly predicted at least 5 percent relative emergence for some or all of the seed collections before any corresponding seedlings emerged. With greater irrigation (fig. 4—fc x 2.00), the model overestimated time to 50 percent relative emergence for some collections, but correctly predicted time of emergence for most of the corresponding collections.

The similarity between hydrothermal time predictions and thermal time predictions (fig. 4) can be explained by two interrelated causes: the relationship between soil water

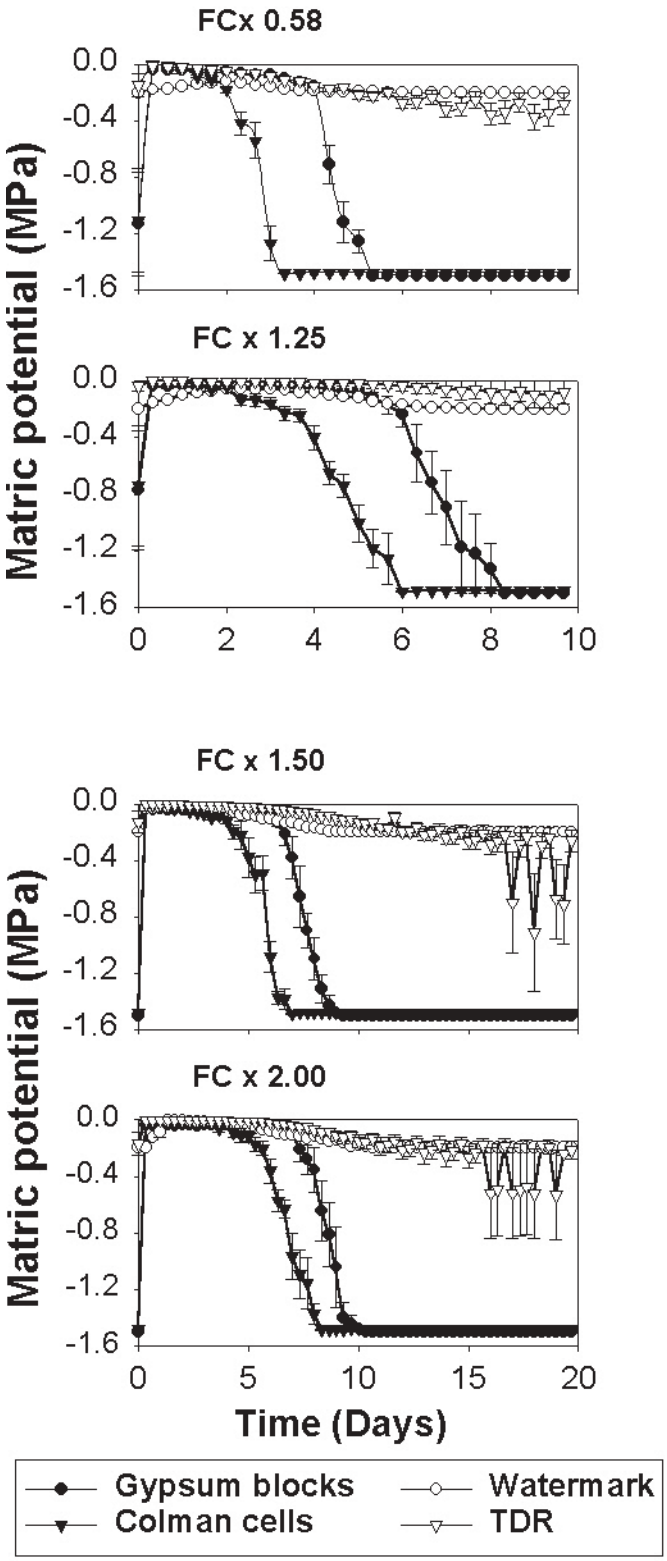

Figure 3—Soil matric potential measured at 1 to 3 cm below the soil surface for different sensors in soil subjected to four irrigation regimes (field capacity x 0.58, 1.25, 1.5, 2.0) and allowed to air dry. Error bars indicate standard error, n = 4.

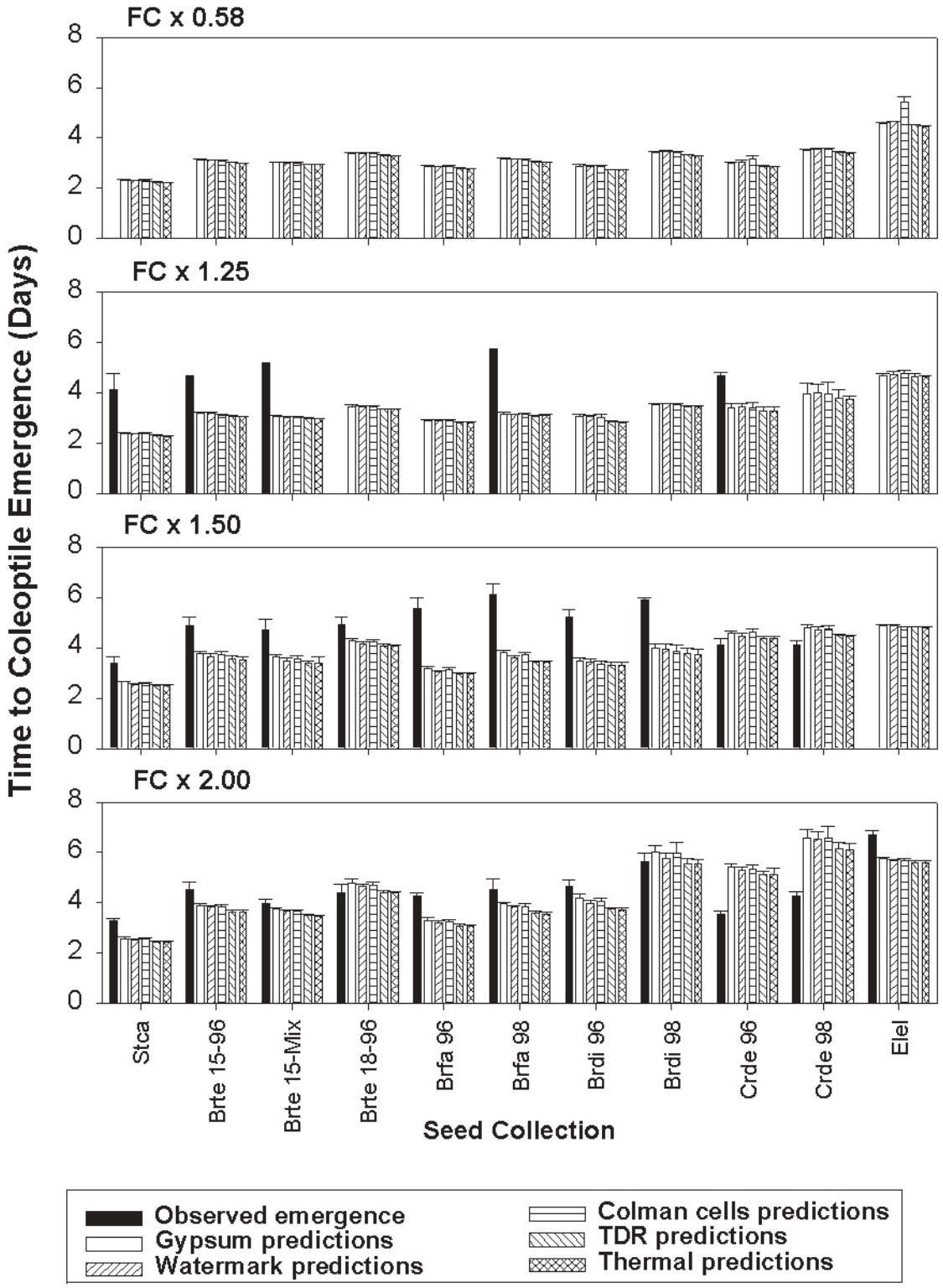

Figure 4—Observed and predicted time to coleoptile emergence. The models predicted 50 percent relative emergence when there was an observed emergence and 5 percent relative emergence when there was no observed emergence using matric potential and thermal inputs for either a hydrothermal time model (matric potential and thermal inputs) or a thermal time model (thermal inputs only) for each seed collection and irrigation regime. Error bars indicate standard error, n = 4.

matric potentials and the period when seeds were germinating and the nature of the hydrothermal and thermal time equations. Seeds germinated within the first 1 to 4 days after the 1.25, 1.50, and 2.00 fc irrigation treatments. During this period, the differences in soil matric potential measurements among the different sensors were minimal, and matric potential values were relatively high (fig. 3). As a result, the differences between $(\Psi–\Psi_{b(g)})$ among each sensor type were minimal. In addition, the influence of $(T–T_b)$ was approximately 10 times greater than the influence of $(\Psi–\Psi_{b(g)})$ or $(–\Psi_{b(g)})$ for the hydrothermal and thermal time equations, respectively. This large difference in the relative contribution made by the thermal portion of the germination models essentially masked small differences in soil water matric potential as measured by each sensor type.

The ability of a hydrothermal time model to accurately predict emergence of seeds under slower germination and drying conditions requires sensors that more accurately measure water potential in the seed zone. Previous research has successfully created models using soil property related parameters to estimate daily soil moisture relationships. Models developed by Finch-Savage and Phelps (1993) are based on soil temperature and soil-type relationships, while Roman and others (2000) used weekly soil moisture averages from TDR sensors to develop near-surface soil moisture relationships. Currently, soil moisture sensors are unable to provide direct soil water potential inputs that accurately predict seedling emergence using a hydrothermal time model. Energy-based heat and waterflow models should be tested to see if they can predict near-surface water potential to provide accurate hydrothermal time predictions of seedling emergence.

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