Emergence Prediction of Common Groundsel (*Senecio vulgaris*)

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Common groundsel is an important weed of strawberry and other horticultural crops. Few herbicides are registered for common groundsel control in such crops, and understanding and predicting the timing and extent of common groundsel emergence might facilitate its management. We developed simple emergence models on the basis of soil thermal time and soil hydrothermal time and validate them with the use of field-derived data from Minnesota and Ohio. Soil thermal time did not predict the timing and extent of seedling emergence as well as hydrothermal time. Soil hydrothermal time, adjusted for shading effects caused by straw mulch in strawberry, greatly improved the accuracy of seedling emergence predictions. Although common groundsel generally emerges from sites at or near the soil surface, the hydrothermal model better predicts emergence when using hydrothermal time at 5 cm rather than 0.005 cm, probably because of the volatility of soil temperature and water potential near the soil surface.

Nomenclature: Common groundsel, *Senecio vulgaris* L.; strawberry, *Fragaria* × *ananassa* Duchesne.
Key words: Base temperature, base soil water potential, Weibull function.

Common groundsel has spread throughout temperate regions and is now a weed of forages, cereals, mint, berries, ornamentals, and vegetables (Agamalian 1983; Holm et al. 1997; Robinson et al. 2003). Control is complicated by tolerance to several herbicides (Doohan and Figueroa 2001; Figueroa and Doohan 2006), resistance to others (Beuret 1989; Fuerst 1984; Mallory Smith 1998; Radosevich and Devilliers 1976; Ryan 1970), and intolerance of rotational crops to many efficacious herbicides (Figueroa et al. 2005). Common groundsel seedlings can emerge over extended periods (Roberts 1982). Consequently, a single application of a nonresidual herbicide is unlikely to control the weed adequately. Furthermore, a soil-applied residual herbicide would need to be timed so that the herbicide is still active and available when most of the common groundsel germinates. Understanding the dynamics of common groundsel seedlings could help improve weed control timing and thus improve the efficacy of control.

Common groundsel emergence in spring occurs after soil temperatures rise and soil is moist. Early weed emergence models have been based on growing degree days, the integral of daily air temperatures above a threshold (Alan and Wiese 1985; Bewick et al. 1988), because temperature is a primary variable regulating both seed dormancy and germination (Roberts 1988) of many temperate weed species. However, recent weed emergence models have integrated soil water potential with soil temperature to calculate hydrothermal time, often with greater predictive success than when temperature is used as the only predictor of weed emergence (Forcella et al. 2000; Grundy 2003; Roman et al. 2000).

Not all soil microclimate conditions control the germination rate of common groundsel seeds in field settings. Common groundsel's small seeds typically emerge from depths of less than 3 cm, where the daily gradients in both soil temperature and moisture are much greater than for deeper soil layers. It might be impossible to measure soil moisture potential at shallow depths. For example, TDR (time domain reflectometry) probes require soil volumes or depths that can extend several centimeters beyond sensor dimensions (Ferre et al. 1998). Numerical simulation is often the only practical way to estimate the microclimate parameters for the germination zone of shallowly buried weed seeds.

Coupled soil moisture and temperature models have been validated in the literature (e.g., Ács et al. 1991; Flerchinger 1987; Hammel et al. 1981; Nagai 2002; Xiao et al. 2006). These theoretical models require numerous input parameters, such as solar radiation or wind speed, which are often unavailable for field sites. To overcome these difficulties, a new coupled-heat water transport model was developed and written in Java (Simplified Heat and Water Transport Model: SHWT). SHWT is based on existing theoretical heat and moisture transport models (e.g., Campbell 1985; Flerchinger 1987; Hammel et al. 1981; Richter 1987) but also includes additional empirical models to ease user input requirements (Arya and Paris 1981; Brooks and Corey 1964; Campbell 1974; Gupta and Larson 1979; Rawls et al. 1982; Saxton et al. 1986; Spokas and Forcella 2006). The modest inputs required of users are daily maximum and minimum air temperatures, daily precipitation, geographical location (latitude, longitude, and elevation), and soil texture information (sand, silt, clay, and organic matter). The user selects the soil depth for which estimates of soil temperature and soil moisture are of interest. SHWT's empirical models estimate the needed soil heat and moisture transport parameters so that heat, liquid water, and water vapor transport can be solved with iterative finite difference calculations.

Our objectives were to develop an empirical seedling emergence model for common groundsel on the basis of daily soil microclimate variables that were simulated for various soil depths. Ultimately, such a model could lead to improved management of common groundsel, especially in high-value horticultural crops.

Materials and Methods

Monitoring Sites. Datasets for timing and extent of seedling emergence were obtained from a published dissertation (Figueroa 2003) and newly collected from field sites. The dissertation data were derived from a field near Kingsville, OH (Table 1), during 2002 and 2003. Seedlings emerging from the soil at this site were counted and removed weekly

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Table 1. Geographical location and soil texture information for the three field sites in this study: Kingsville in Ohio and SLRF (Swan Lake Research Farm) and WCROC (West Central Research and Outreach Center) in Minnesota.

Site	Latitude	Longitude	Elevation	Sand	Silt	Clay	OM
			m	(%)			
SLRF	45°41′N	95°48′W	360	36	36	28	2.8
WCROC	45°35′N	95°52′W	348	45	35	20	3.7
Ohio	41°53′N	80°04′W	240	80	10	10	1.8

from May through mid-October. The soil type was a Bogart loamy fine sand (Aquic Hapludalf) with 1.8% organic matter, and it was field cultivated to 7 cm depth in late April and mid-September each year. Associated daily weather information was downloaded from the database of the Ashtabula Agricultural Research Station (http://www.oardc.ohio-state.edu/centernet/stations/grhome.asp), which is 1.5 km from Kingsville.

Original data also were collected at two field sites near Morris, MN (Table 1). The first was the field used for strawberry variety trials at the West Central Research and Outreach Center (WCROC) of the University of Minnesota. The soil was a Barnes loam (Pachic Udic Haploboroll) with 3.7% organic matter. In this field four quadrats 25 by 40 cm were placed in each of three randomly distributed plots. Plot dimensions were 1.2 by 3.1 m and contained a single central row of strawberries. Each quadrat was centered on a strawberry row. Seedlings of common groundsel were counted and removed twice weekly from each quadrat during the main emergence period of 2006, and then only periodically until early autumn. The experimental site was located approximately 300 m from the WCROC's weather station.

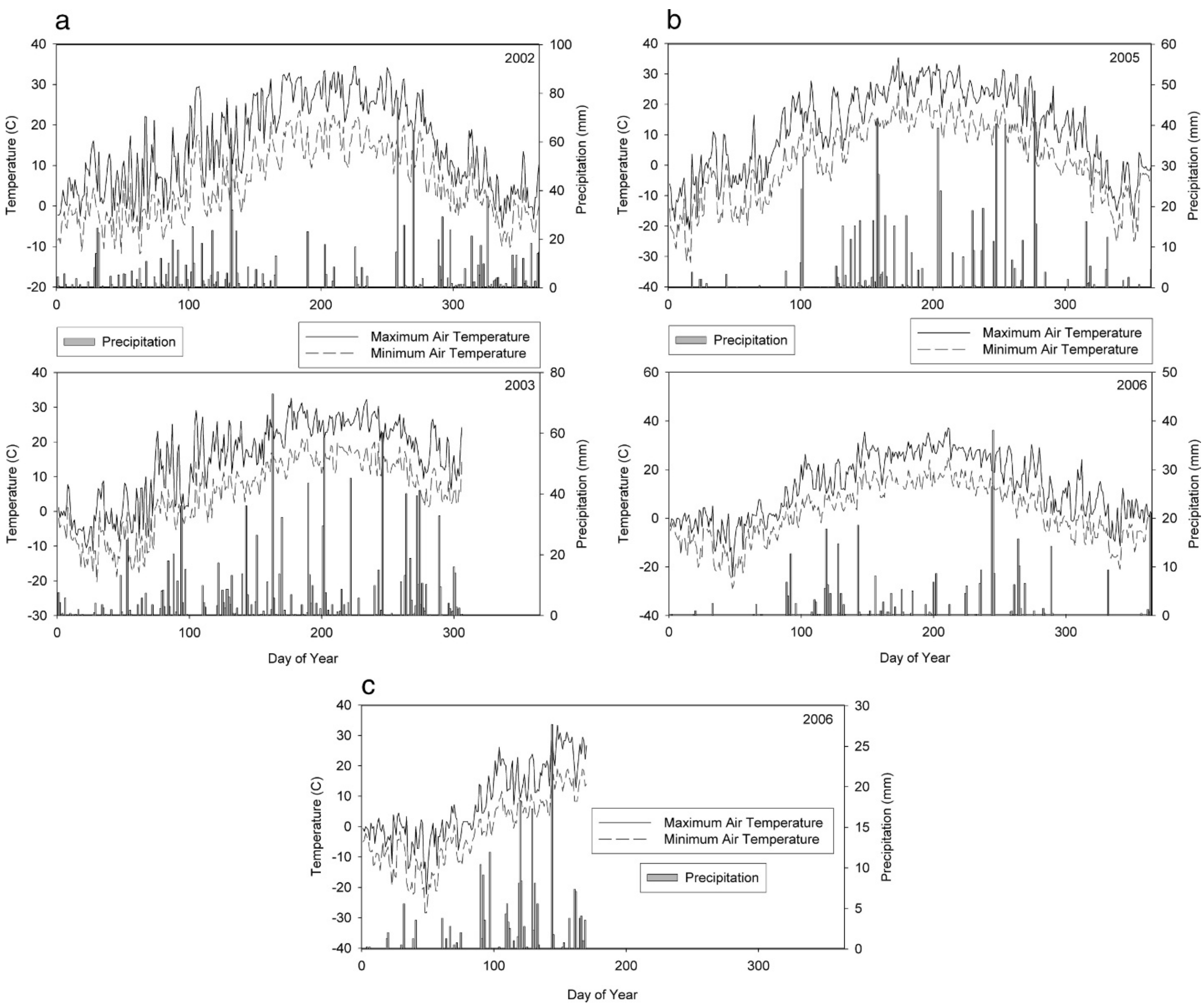

Figure 1. Weather station air temperature and precipitation data for (a) Kingsville, OH (OH) in 2002 and 2003, (b) Swan Lake Research Station (SLRF; Morris, MN) in 2005 and 2006, and (c) West Central Research and Outreach Center (WC; Morris, MN) in 2006.

The second field was at the U.S. Department of Agriculture (USDA)—Agricultural Research Service's Swan Lake Research Farm (SLRF; 45°41′N, 95°48′W, 360 m elevation). The specific location was the farm's weather station. Four 25-cm-tall polyvinylchloride (PVC) tubes were buried 20 cm deep in soil in the early spring of 2005, and an additional four were buried in late autumn of 2005. The 10-cm-diam tubes were filled with 20 cm of Barnes loam soil. Soil was compacted to a bulk density of 1.3, which left a 5-cm-tall rim above the inside and outside soil surfaces. The soil inside the tube had previously been inoculated with 200 common groundsel seeds in spring and 300 seeds in autumn. Seeds were uniformly distributed throughout the soil profile in the tubes. The sources of these two sets of seeds were from flower beds at the University of Minnesota–Morris campus and the strawberry plots at WCROC, respectively. Seed collection sites were separated from one another by about 2 km. Seedlings of common groundsel were counted and removed twice weekly from each PVC tube during the flush of emergence in the springs of 2005 and 2006, and then only periodically until early autumn.

Weather Data and Simulations. Daily average soil moisture potential and temperatures were simulated with the SHWT model (Spokas, unpublished data). SHWT requires minimal meteorological data (i.e., daily maximum and minimum air temperature and precipitation; Figure 1), along with geographical location and soil texture (Table 1). SHWT also has the ability to simulate both direct sun and shaded soil locations. All locations were simulated as having direct sun, with the exception of WCROC, where the shaded option was used to account for straw mulch covering the soil. Outputs from the SHWT model were daily average soil temperatures and soil water potentials for 50 nodes at geometric soil depth spacings from 0 to 2 m.

Common Groundsel Model Development. The common groundsel emergence model was based on the hydrothermal time (HTT) concept (Bradford 2002), defined as an integration of soil moisture potential limits and thermal time (θ_T). Hydrothermal time was calculated daily, as described by Roman et al. (2000),

$$\mathrm{HTT} = \sum_{d=1}^{n} \theta_H \theta_T \qquad [1]$$

where $\theta_H = 1$ when $\Psi > \Psi_b$; otherwise, $\theta_H = 0$; $\theta_T = T - T_b$ when $T > T_b$, otherwise $\theta_T = 0$; Ψ symbolizes average daily soil moisture potential, Ψ_b is base soil moisture potential, T is average daily soil temperature, T_b is base temperature, HTT is the hydrothermal time (in degree days), and d is the time step in days. HTT was accumulated only on days when Ψ was greater than Ψ_b and when T was greater than T_b.

To simulate the conditions seeds would experience at the soil surface and deeper, simulated soil moisture and temperature profiles were used for depths of 0.005 and 5 cm. The base temperature threshold for common groundsel emergence was initially set at 1.75 C (Spokas and Forcella, unpublished data). The base soil moisture potential was determined by iterating a set of water potentials until the best match was achieved with the Ohio data. Data from the two Minnesota sites were used as model validation sets. Because common groundsel is known to germinate near the soil surface after rainfall, the initial water potential was set preliminarily at 0 MPa and then reduced by increments of 0.1 MPa until the maximum fit with the field data was reached. The optimum base soil moisture potential found through this iterative process was −0.5 MPa. This base soil water potential was used in calculating HTT for both depths.

Hydrothermal time was accumulated daily during the growing season of each experiment-year. Percent seedling emergence for each experiment-year was calculated and normalized to 100%. To predict the pattern of seedling emergence, percent cumulative emergence values were predicted with the use of hydrothermal time as input for the Weibull function,

$$Y = M\left[1 - e^{-k(\mathrm{HTT}-z)^c}\right] \qquad [2]$$

where Y is cumulative percent emergence at a cumulative HTT value, M is the asymptote (theoretical maximum for Y normalized to 100%), k is rate of increase, z is the lag phase, and c is a curve shape parameter. The parameters (k, z, and c) in the Weibull function were estimated by nonlinear regression (PROC NLIN) that used the Gauss–Newton algorithm in SAS (1995). The function was initialized with k and c set to 0.001 and 0.1, respectively. The parameter z was iteratively estimated by values from 50 to 165. The iterative parameter estimation algorithm proceeded by increments of 0.001 for k and 0.1 for c.

Statistical Evaluation. Model performance equations and their rationale are discussed in Spokas and Forcella (2006), as well as Legates and McCabe (1999). The modeling index (d) varies between 0 and 1, with a value of 1 indicating complete agreement between model predictions and the observed data. Modeling efficiency (ME) values range from negative infinity to 1, with 0 indicating that the observed mean is as good a predictor as the model, whereas negative values show the mean to be a better predictor than the model (Legates and McCabe 1999). Root mean square error (RMSE) and mean absolute error (MAE) have the same units as the observed data (e.g., percent emergence per degree day) and are both recommended measures of model performance (Willmott 1982, 1985).

Results and Discussion

All sites displayed a temperature progression typical of temperate climates (Figure 1). Winter lows were 0 C and below, rising in the spring toward summer highs of more than 30 C. Both years in Ohio had a similar pattern of rising temperatures during the spring, but summer precipitation varied with a drought throughout July and August of 2002 and abundant summer rains in 2003. Temperatures in Minnesota were lower early in 2006 than 2005, resulting in a more rapid temperature rise throughout spring 2006. Precipitation was similar for both Minnesota locations, although less than what was recorded in Ohio.

The relationship between common groundsel emergence and temperature was tested initially with a simple growing degree day (GDD) model (i.e., temperature accumulation above a 1.75 C threshold). Figure 2 illustrates all five data sets compared with GDD. If a single and simple GDD model

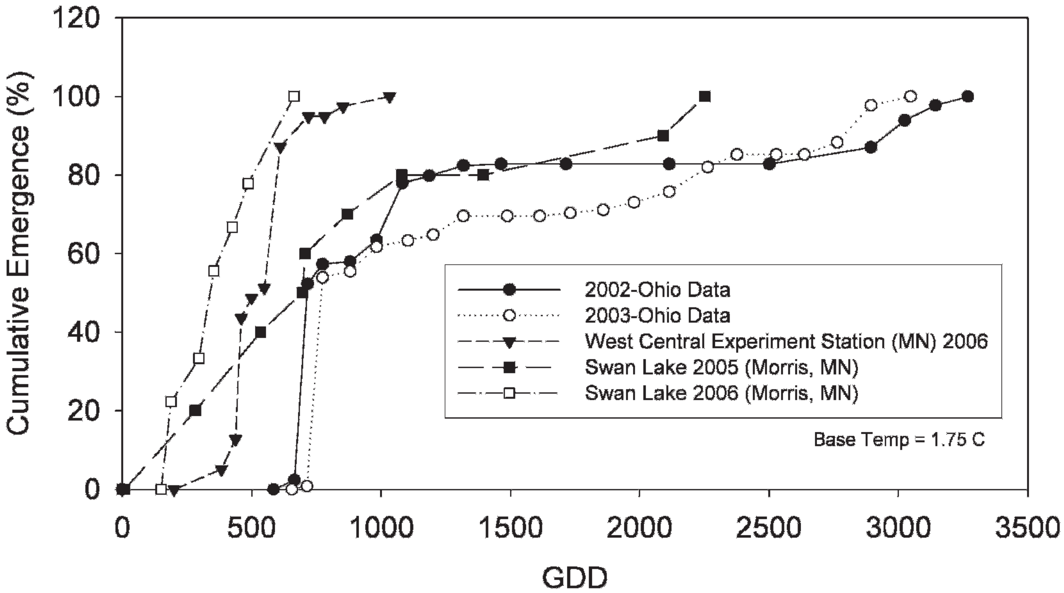

Figure 2. Percent cumulative emergence vs. growing degree days (GDD) for the OH and MN field sites.

could explain common groundsel emergence, these data sets would have superimposed upon one another or at least overlapped more than is apparent in Figure 2.

There was an apparent relationship between temperature, rainfall (Figure 1), and common groundsel emergence (Figure 2). In Ohio, cumulative emergence gradually increased with the frequent rains of 2003 but rose more abruptly after the occasional precipitation events of 2002. The steeper rise in emergence in Minnesota in 2006 matched the sharper rise in spring temperatures at both Minnesota sites, whereas the gradual increase in temperatures during the spring of 2005 led to more gradual emergence. This gradual rise also is coupled to more frequent precipitation events in 2005. The 2005 emergence data from the SLRF were similar to that for 2002 and 2003 in Ohio, but different from the pattern of emergence in either Minnesota location in 2006 (Figure 2). For both years in Ohio and the 2005 SLRF data, 50% cumulative emergence occurred near 700 GDD. However, for both Minnesota sites half of all the common groundsel seedlings in 2006 had emerged by 500 GDD, and nearly all seedlings emerged by 700 GDD (Figure 2).

Model performance statistics confirm a relationship between observed and predicted emergence for the simple GDD model when used to predict emergence in Ohio, but poor predictability for the Minnesota datasets (Table 2). The *d* statistic was 0.92 for 2002 Ohio data, 0.77 for 2003, and 0.86 for the combined data set. Model performance statistics show that the GDD model worked best at the SLRF in 2005 and performed poorly in 2006 at SLRF and WCROC. The negative values for ME for 2003 Ohio and all the Minnesota data sets indicated that using simply the mean of the observed cumulative emergence data at each location to predict emergence would have been more accurate than the GDD model. The RMSE and MAE values followed a similar pattern, showing a better model fit of the GDD model to the data for 2002 than 2003, with intermediate results for the combined data set.

To overcome lack of predictability of the GDD model for SLRF and WCROC data, an HTT model was developed from the Ohio data. The HTT model with the experimentally derived (Spokas and Forcella, unpublished data) common groundsel emergence temperature threshold of 1.75 C reasonably predicted emergence when the SHWT estimations for daily average soil moisture potential and temperatures at the 5-cm soil depth were used (Figure 3). The 5-cm model accurately predicted 50% common groundsel emergence in

Table 2. Model performance statistics for the growing degree day (GDD) model, hydrothermal time (HTT) model at soil depths of 0.005 (Equation 3) and 5 cm (Equation 4). Locations are Kingsville in Ohio and SLRF (Swan Lake Research Farm) and WCROC (West Central Research and Outreach Center) in Minnesota. Analyses for 2002 and 2003 or 2005 and 2006 used data from both years to fit the models. A shade algorithm was used for the HTT models at the WCROC location to simulate the effect of straw mulch on soil microclimate.

		d			ME			RMSE			MAE		
Location	Year	GDD	HTT 0.005 cm	HTT 5 cm	GDD	HTT 0.005 cm	HTT 5 cm	GDD	HTT 0.005 cm	HTT 5 cm	GDD	HTT 0.005 cm	HTT 5 cm
Ohio	2002	0.92	0.87	0.89	0.60	0.39	0.67	20.10	24.86	18.17	12.17	15.73	15.11
	2003	0.77	0.53	0.97	−0.66	−0.10	0.90	26.21	21.33	9.08	19.62	18.80	7.37
	2002 2003	0.86	0.84	0.92	0.21	0.24	0.71	23.51	23.07	14.29	16.09	17.35	11.40
SLRF	2005	0.75	0.91	0.95	−0.46	0.55	0.81	36.45	23.41	15.10	26.83	17.39	11.10
	2006	−2.54	0.92	0.95	−2.54	0.55	0.81	59.98	17.60	13.81	50.79	14.44	10.51
	2005 2006	0.50	0.88	0.94	−1.33	0.42	0.77	47.57	23.26	15.02	36.79	15.41	11.64
WCROC	2006	−0.55	0.84	0.78	−2.62	0.27	0.59	65.22	29.41	22.13	55.46	23.36	20.15

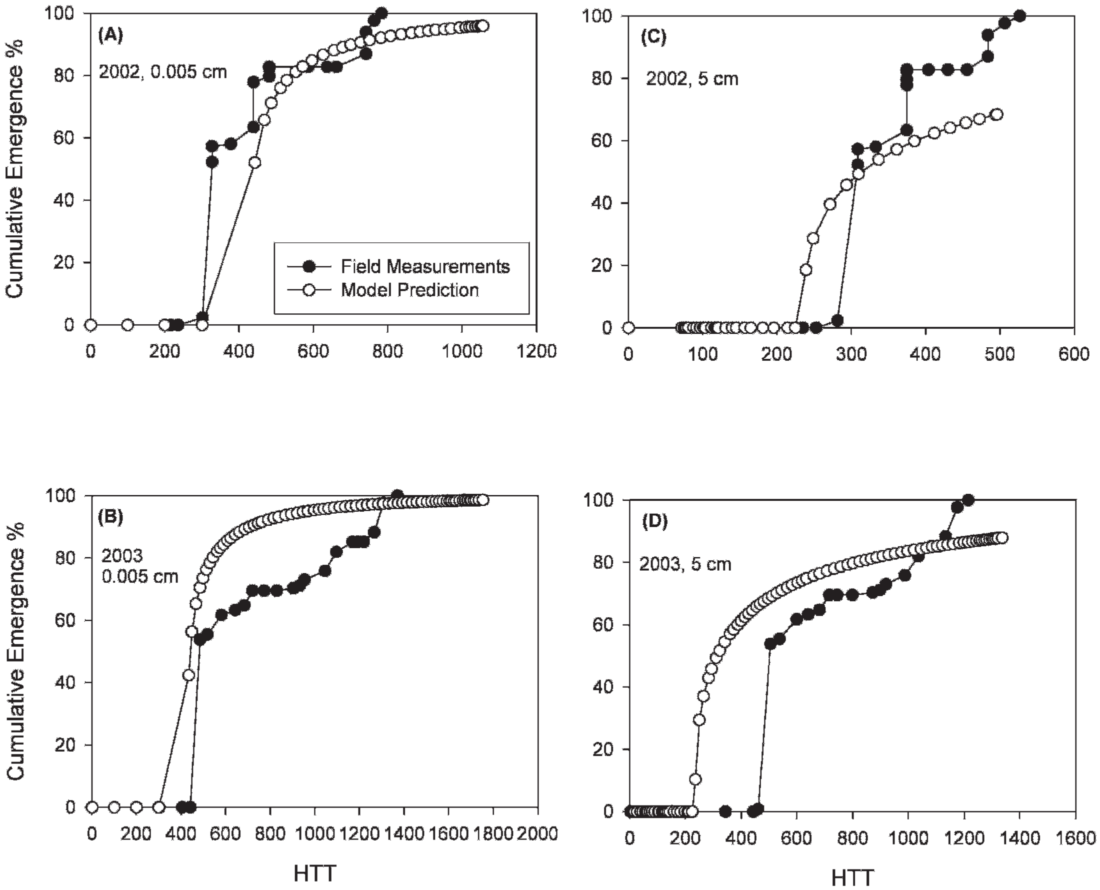

Figure 3. Kingsville, OH, observed and Weibull function predictions of common groundsel emergence for the 0.005-cm soil depth in (A) 2002 and (B) 2003 and for the 5-cm soil depth in (C) 2002 and (D) 2003 vs. hydrothermal time (HTT).

2002 but somewhat overpredicted emergence for the 2003 Ohio data. Initial testing with the SHWT soil moisture and temperature estimates for the 0.005-cm soil profile depth found that the hydrothermal model parameters could not be estimated because of a lack of convergence when the 1.75 C common groundsel emergence temperature threshold was used (data not shown). Iteratively testing emergence threshold temperatures from −10 to 10 C found that an emergence threshold of 0.0 C resulted in the best emergence predictions. The parameterized 0.005-cm model predicted 50% common groundsel emergence as occurring 100 HTT later than was observed in 2002 (Figure 3A) but was within 10 HTT of the observed 50% emergence date in 2003 (Figure 3B). Late season predictions were within 5% of the observed emergence in 2002, but the 0.005-cm model tended to underpredict late season emergence in 2003.

Equations 3 and 4 represent the HTT model with parameters derived from the 2002 and 2003 combined Ohio data set.

$$0.005\text{cm} \qquad Y = 100\left[1 - e^{-0.40(\text{HTT}-426.1)^{0.239}}\right] \qquad [3]$$

and

$$5\text{cm} \qquad Y = 100\left[1 - e^{-0.42(\text{HTT}-234.6)^{0.110}}\right] \qquad [4]$$

The parameterized HTT models (Equations 3 and 4) were validated with the SLRF and WCROC data for both the 0.005- and 5-cm soil depths (Figures 4 and 5). For SLRF, both HTT models predicted initial emergence 200 HTT units later than observed and a more rapid increase in emergence during the middle of the season (Figure 4). Both *d* and ME statistics indicated a good fit, with *d* values from 0.88 to 0.92 when soil data from the 0.005-cm depth was used, and *d* values of 0.94 to 0.95 for data from the 5-cm depth. The higher *d* and ME and lower RMSE and MAE values for the 5-cm depth model generally indicate better model performance than for the 0.005-cm soil depth.

The same HTT model predicted common groundsel emergence 200 HTT later than was observed at the WCROC location (Figure 5). The shade algorithm of the SWHT model was then used to simulate the effect that straw mulch would have had on soil temperature at the WCROC site because the observed groundsel seedlings had to emerge through either mulch or the strawberry canopy. Simulated shaded soil temperatures were consistently less than those for bare soil at the 0.005-cm depth (Figure 6), but less different at the 5-cm depth (not shown). The major difference was divergence in the predicted soil moisture values, which are shown in Figure 6B for the 0.005-cm depth. Evaporation is less from the surface and soil moisture potential values higher in the shaded simulation. Accounting for this shading effect with the predicted moisture and temperatures greatly improved prediction of common groundsel emergence at the WCROC site with the HTT model. HTT model performance statistics indicate a reasonable fit to the

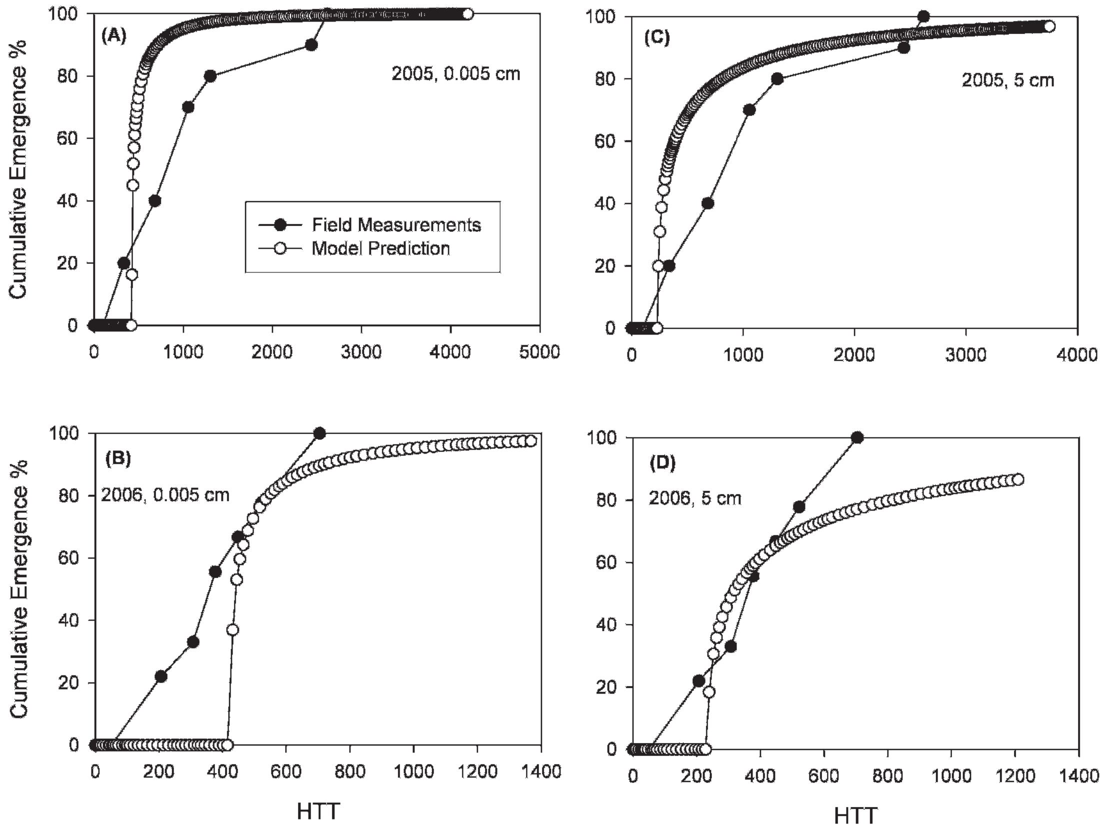

Figure 4. The Weibull function parameterized with Kingsville, OH, data and validated for prediction of common groundsel emergence at the Swan Lake Research Farm, MN (SLRF), vs. hydrothermal time (HTT). Model parameters for the 0.005-cm soil depth in (A) 2005 and (B) 2006 and for the 5-cm soil depth in (C) 2005 and (D) 2006.

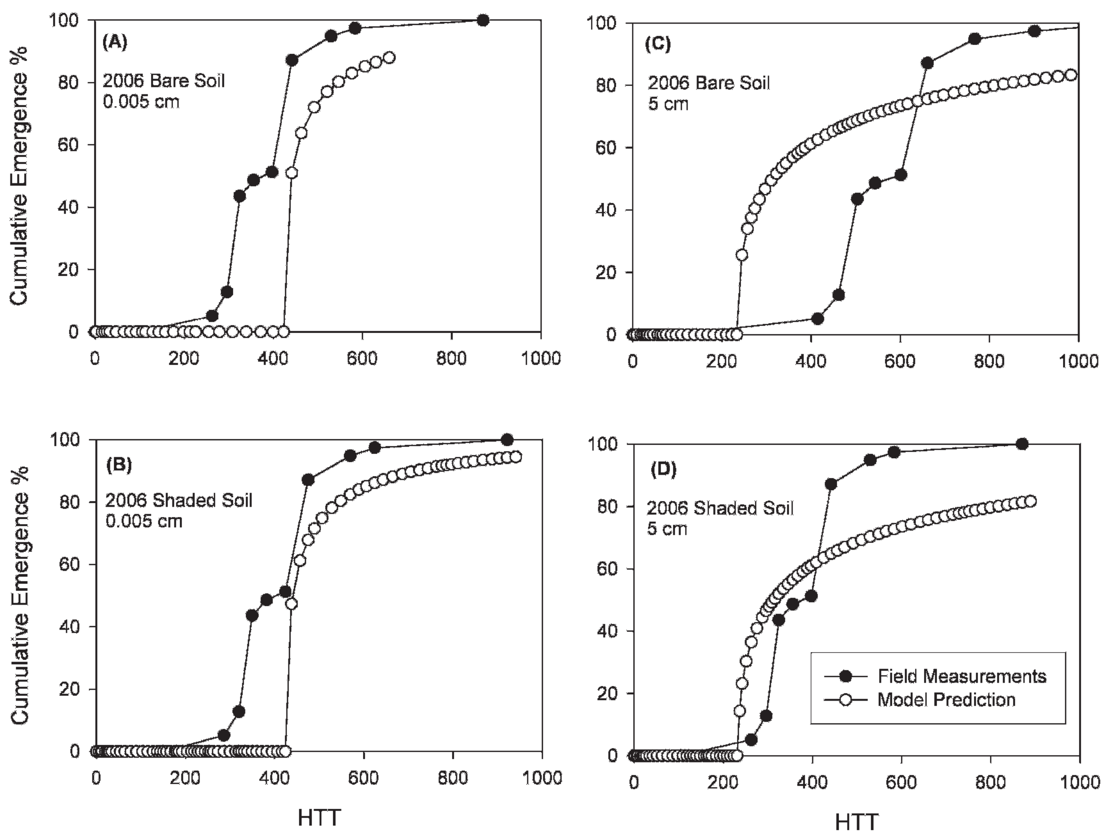

Figure 5. The Weibull function parameterized with Kingsville, OH, data and validated for prediction of common groundsel emergence in 2006 at the West Central Research and Outreach Center (WC) in Morris, MN, vs. hydrothermal time (HTT). Weibul function parameters for the 0.005-cm soil depth in (A) bare soil and (B) shaded soil and for the 5-cm soil depth in (C) bare soil and (D) shaded soil.

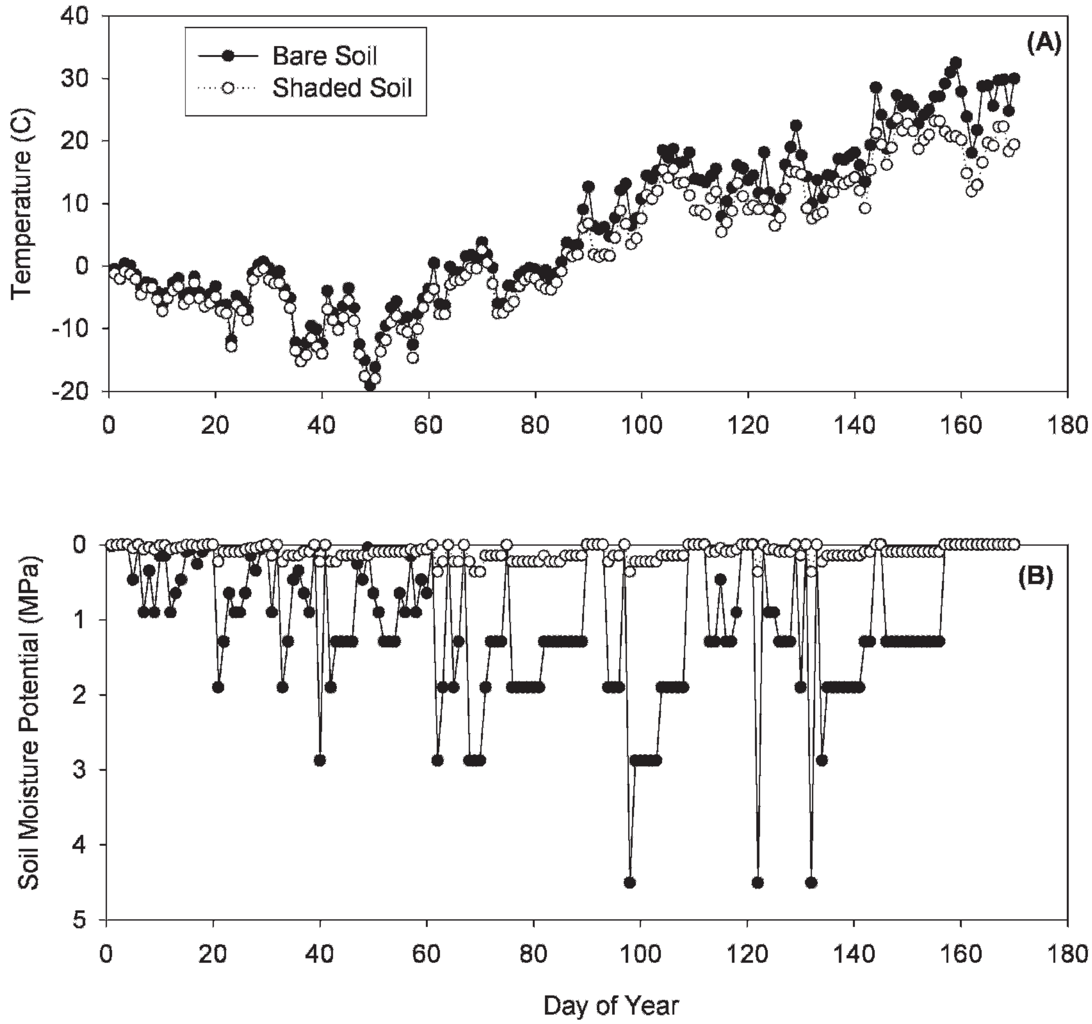

Figure 6. SHWT model predictions for daily average (A) soil temperature and (B) soil moisture potential for either bare ground or a straw mulch-shaded surface for the 0.005-cm depth.

data at either depth, with the 5-cm depth model performing better than the consistently underpredicting 0.005-cm depth model.

With the SHWT model, we were able to simulate soil moisture and temperature so that the HTT model reasonably simulated emergence of common groundsel in strawberry. The improvement was appreciable when compared with the simpler GDD model. Although common groundsel generally germinates only when shallowly buried, the HTT model more accurately predicted common groundsel emergence when based on conditions at 5 cm than at 0.005 cm. The reason for this could be the current inability to predict near-surface soil conditions accurately. Simulation of shading under straw mulch allowed extension of the model beyond bare ground situations, and this potentially could improve simulation of weed emergence in reduced tillage and other cropping systems. The HTT models developed here have sufficient accuracy to increase the efficacy of herbicides by improving the decision-making process for the timing of (1) preemergence applications immediately before emergence and (2) postemergence applications until a majority of common groundsel seedlings emerge. Accurate prediction of emergence could also reduce grower costs by reducing the need for hand weeding and other weed control practices.

Acknowledgments

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