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Seedling emergence model for tropic ageratum (*Ageratum conyzoides*)

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The timing of weed seedling emergence relative to the crop is important in planning and optimizing the time of weed control, but very little work has been done to predict seedling emergence of tropical weed species, especially in low-input and small-scale farms. We developed a simple model based on hydrothermal time to predict seedling emergence of tropic ageratum. Hydrothermal time at 2-cm soil depth was calculated from soil moisture and soil temperature simulated from several micrometeorological and soil physical variables. The model was developed using 5 yr of field emergence data from a continuous corn–cassava production system in southwestern Nigeria. Percentage of cumulative seedling emergence from the 5-yr data set was fitted to cumulative soil hydrothermal time using a Weibull function. The predicted cumulative emergence curve significantly matched observed field emergence (r^2 = 0.83). Model predictions were evaluated with root mean square error (RMSE) using four field emergence data sets from southeastern Nigeria (RMSE ≤ 10.1) and Los Banos, Philippines (RMSE = 8.9). RMSE values ≤ 10 indicated that predictions represented observations well. With such models, extension personnel working on tropical soils, especially in West Africa, may be able to provide additional advice to farmers on the appropriate time for the management of tropic ageratum.

Nomenclature: Tropic ageratum, *Ageratum conyzoides* L. AGECO; cassava, *Manihot esculenta* Crantz; corn (maize), *Zea mays* L.

Key words: Hydrothermal time, phenology, simulation, soil moisture, soil temperature, tropical weed.

Tropic ageratum is an erect or decumbent annual weed (Akobundu and Agyakwa 1998) that occurs in many countries of the world, especially in tropical and subtropical regions. It is a major weed in many annual (Rafey and Prasad 1995; Singh and Saha 2001; Wezel 2000) and perennial (Devi et al. 1993; Ndubizu 1987) crops and has been reported as host of many crop diseases (Ijani et al. 2000; Kashina et al. 2003; Pabitra et al. 1997). Previous studies show that tropic ageratum constitutes more than 70% of the total above- and belowground weed populations in farms where it occurs (Akobundu et al. 1999; Devi et al. 1993; Garcia 1995). The potential to produce many seeds (94,772 seeds plant^{-1}) and to shed seeds over extended times (5 to 8 mo), as well as its extraordinary physiological plasticity, has enhanced its persistence in arable fields (Ekeleme et al. 2000; Mortimer 1989; Rodriguez and Cepero 1984). Although some studies have demonstrated allelopathy in the weed (Bhatt et al. 2001; Kato-Noguchi 2001), shoot competition for light appears to be the major mode of interference in crops (Banyikwa and Rulangorang 1985), and this is enhanced by its ability to emerge in abundance (> 1,000 plants m^{-2}) (Anonymous 2000).

Early weed emergence relative to the crop allows weeds to compete better with crops. Many authors (Chikoye et al. 1995; Knezevic et al. 1997; Moechnig et al. 2003) have reported that the magnitude of crop yield losses from crop–weed competition, among other factors, depends on the time of weed seedling emergence relative to that of the crop. For example, Knezevic et al. (1997) reported that the time of redroot pigweed (*Amaranthus retroflexus* L.) emergence relative to sorghum [*Sorghum bicolor* (L.) Moench] leaf stage was critical for the outcome of sorghum–pigweed competition because significant sorghum yield losses occurred when redroot pigweed emerged before the five-leaf stage of sorghum.

Hence, to control weeds adequately, especially with limited use of herbicides, farmers need to know the timing and extent of weed seedling emergence before and during the growing season. Armed with such knowledge, farmers can better time the allocation of their resources and energies to actual weed problems, either through hand labor, draft animals, and mechanized implements or through herbicides. Knowledge of when weeds emerge is equally applicable and beneficial to all forms of weed-management technologies.

A number of models for predicting weed emergence patterns of some weed species have been developed (Forcella 1998; Grundy and Mead 2000; Oryokot et al. 1997a, 1997b; Roman et al. 2000). The first-generation models for predicting weed emergence were based on the thermal time (growing degree days) concept (Alan and Wiese 1985; Bewick et al. 1988). In these models, mean air or soil temperatures are accumulated daily until emergence occurs. Recent weed emergence models are based on the concept of integrating soil water potential and soil temperature (hydrothermal time) (Forcella 1998; Grundy 2003; Roman et al. 2000), and they have achieved some level of success (Forcella et al. 2000). So far, however, most of the models developed to understand and predict weed emergence are for temperate weed species. Very little has been published on the prediction of tropical weed species emergence. Indeed, whether the major variables affecting emergence, such as soil temperature, in tropical species are the same as in temperate species is not yet known. Consequently, the objective of this study was to develop a model that would predict tropic ageratum seedling emergence using microclimate data and to evaluate the ability of the model to estimate emergence in different locations.

Materials and Methods

Field Experiments Used in Model Construction

Emergence values of tropic ageratum were collected from field experiments established in 1994, and 1997 through 2000 at the International Institute of Tropical Agriculture (IITA) Research Farm, Ibadan, southwestern Nigeria (7°30′N, 3°54′E). The site is located within the humid forest–savanna transition zone with mean annual temperature of 26 C and average annual precipitation of 1,250 mm. The soil is sandy loam (Oxic Paleustalf: 70% sand, 13% silt, 17% clay, 2% organic matter, and pH 6.2). The experimental site was a long-term fallow management trial established in 1989 as a split plot with three main-plot and four subplot treatments. Main-plot treatments were (1) natural bush fallow, (2) alley cropping with leucaena [*Leucaena leucocephalla* (Lam.) de Wit], and (3) live mulch with tropical kudzu [*Pueraria phaseoloides* (Roxb.) Benth.]. Subplot treatments were cropping intensities: (1) continuous cropping and 1 yr cropping followed by (2) 1, (3) 2, and (4) 3 yr of fallow. All treatments were replicated three times.

Emergence values from the continuously cropped natural bush fallow treatment were used for this study. This treatment represents the dominant cropping system in West Africa. At the beginning of each cropping season (usually late April to early May), the vegetation was manually cleared. Cassava 'TMS 30572' cuttings, about 25 cm long each, were planted at a density of 10,000 stems ha^{-1} in rows that were 100 cm apart and at a within-row spacing of 100 cm on May 4, 1994; May 1, 1997; April 27, 1998; May 3, 1999; and May 2, 2000. Corn 'TZSRW' was sown at the same time and in the same rows as cassava but at a population of 40,000 plants ha^{-1} with a within-row spacing of 25 cm. Plots were hand hoed to a soil depth less than 10 cm. No herbicides or fertilizers were applied to the plots. Tropic ageratum seedling emergence was monitored fortnightly in two 0.5-m^2 permanent quadrats in each plot starting on May 18, 1994; May 15, 1997; May 11, 1998; May 17, 1999; and May 16, 2000. At each assessment date, seedlings of ageratum that emerged were counted and pulled. Seedlings of other species within the quadrats also were removed. Daily weather data were obtained from the IITA automated weather station located approximately 500 m from the experimental site.

Model Development

Soil moisture and soil temperature of the upper 2 cm of soil depth were simulated with the Simultaneous Heat and Water (SHAW) Model (Flerchinger 2000). Daily maximum and minimum temperature, dew point, wind run, rainfall, and solar radiation were used as microclimate input variables in the SHAW model. Soil physical variables used in the model were 17% clay, 70% sand, 13% silt, 2.0% organic matter, and 1.1 g cm^{-3} bulk density. To correspond with the hot and dry portions of the year in Nigeria, initial soil temperature and water content were set to 30 C and 1% (v/v), respectively, in the model. The estimates of soil temperature and soil water by the SHAW model were accepted as realistic, although their accuracies under Nigerian conditions are unknown.

The depth of 2 cm was chosen because seed bank studies at the same experimental site (data not shown) show greater emergence of annual weed species at 2-cm soil depth than at lower depths (i.e., surface > 2 > 5 > 10 cm). Ismail et al. (2002) also reported higher emergence of seedlings of another annual tropical weed, goosegrass [*Eleusine indica* (L.) Gaertn.], at 2-cm depth than at lower soil depths. Percentage of seedling emergence for each experiment year was calculated and normalized to 100%.

The development of the model was based on the hydrothermal time (θ_{HT}) concept (Bradford 2002), defined as an integration of hydrotime (θ_H) and thermal time (θ_T). More formally, hydrothermal time, calculated daily (d), was described by Roman et al. (2000) as

$$\theta_{HT} = \sum_{d=1}^{n} \theta_H \theta_T \qquad [1]$$

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 water potential, Ψ_b is base soil water potential, T is average daily soil temperature, and T_b is base temperature. In summary, θ_{HT} was accumulated only on days when Ψ was greater than Ψ_b and T was greater than T_b.

The base soil temperature and base soil water potential were determined by iterating a set of temperatures (20 to 30 C, at 1 C intervals) and water potentials (−0.10 to −0.01, at 0.01-MPa intervals) in Equation 1 until there was a maximal fit between cumulative hydrothermal time and percentage of cumulative emergence for each of the experiment years. (Best fit was obtained when T_b and Ψ_b were 28 C and −0.02 MPa, respectively.) The temperatures used in the iteration were based on monthly air temperature ranges at the experimental site and the fact that average minimum daily air temperatures in Nigeria rarely are less than 20 C, whereas the water potentials used in the iteration were based on earlier controlled germination studies on tropic ageratum, in which Sauerborn and Koch (1988) observed that an osmotic potential of −0.10 MPa inhibited seed germination of ageratum. This latter report also showed that when incubated for 35 d, tropic ageratum seeds from West Samoa could germinate, but only minimally, at temperatures as low as 15 C.

Hydrothermal time was accumulated daily for each experiment year, beginning on April 1, 1994 and 1998; March 1, 1997; May 1, 1999; and April 30, 2000. The differing dates reflect times at which soils in the experimental sites were cultivated. To predict the pattern of seedling emergence, the percentage of cumulative emergence values were compared to hydrothermal time with the Weibull function:

$$Y = M[1 - \exp(-k(\theta_{HT} - z)^c)] \qquad [2]$$

where Y is the cumulative percentage of emergence at a cumulative hydrothermal time (θ_{HT}) value, M is the asymptote (theoretical maximum for Y normalized to 100%), k is the rate of increase, z is the lag phase, and c is a curve shape parameter. For estimation purposes, k was parameterized as $k = (1/a)^c$. The parameters (a 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 1.95, respectively. The parameter z was estimated by iterative inspection using values from 0 to 100.

Model Evaluation in Umudike

A dilemma faced by emergence investigators involves the proper method for monitoring this important aspect of a weed's life cycle. We attempted to answer the question of whether removal of early-emerged seedlings affects emergence of later seedlings, while simultaneously using these data to evaluate the emergence model.

Data on seedling emergence of tropic ageratum were collected in 2002 from a field experiment at the Research Farm of Michael Okpara University of Agriculture, Umudike, in southeastern Nigeria (5°22′N, 7°30′E). Umudike is located in the humid forest zone with 2,351 mm average annual rainfall and 27 C mean temperature. The soil is sandy clay loam (Dystric Luvisol: 77% sand, 12% clay, 11% silt, < 1% organic matter, and pH 5.7). A field experiment was established as a randomized complete block design with four replications and four treatments. The treatments were (1) count and tag intact ageratum seedlings, (2) count and remove ageratum seedlings, (3) count ageratum seedlings and kill them with paraquat (0.30 kg ha^{-1}), and (4) within a corn crop, count and remove ageratum seedlings. No crop was sown in the first three treatments. Each plot was hand hoed to < 10-cm soil depth. Seedling emergence was monitored in four 0.25-m^2 permanent quadrats in each subplot. Seedlings of other weed species in the quadrats also were removed.

Daily soil moisture and temperature of the upper 2 cm of soil depth were simulated as described above. Required weather data were obtained from the National Root Crops Research Institute Meteorological Station located approximately 700 m from the experimental site.

Model Evaluation in Los Banos

One assessment of the utility of a model is whether its predictions match observations made in settings far removed from where the model was developed. Toward this end, seedling emergence values for tropic ageratum collected from an upland irrigated rice (*Oryza sativa* L.) field at the International Rice Research Institute (IRRI), Los Banos, Philippines (14°10′N, 121°15′E), in 1985 were obtained from Zimdahl et al. (1988). These authors reported the soil at the experimental field as an association of Lithic and Andeptic Hapludolls, mixed isohyperthermic, with 18% sand, 36% clay, 46% silt, 2.1% organic matter, and pH 5.1. The authors also reported the experimental design, field, and cropping history of the site. Experimental plots were rototilled with a garden tiller, and no crop was present during the assessment of emergence. Daily soil moisture and soil temperature of the upper 2-cm soil depth were simulated from microclimatic data obtained from the Climate Unit of IRRI.[1] Values for soil bulk density (1.11 g cm^{-3}) and saturated hydraulic conductivity (1.0 cm d^{-1}), which were reported by Wopereis et al. (1993) for a similar soil at the same experimental site, were used in the simulation.

For data from both Umudike and Los Banos, root mean square error (RMSE) was used to examine model performance (i.e., agreement between predicted and observed values). RMSE was calculated as $\Sigma([P - O]^2 N^{-1})^{0.5}$ (Roman et al. 2000), where P, O, and N represent values predicted by the emergence model, observed values, and total number of paired values, respectively. Smaller RMSE values indicate better agreement between predictions and observations than larger RMSE values, and an arbitrarily chosen RMSE value of ≤ 10 was considered to represent an adequate fit between predictions and observations.

Results and Discussion

Observed Emergence

The relationships between calendar dates, hydrothermal time, and cumulative field seedling emergence at the three locations are represented in Figure 1. At Ibadan, the hot dry period of the year is between January and April. Thus, assessment of seedling emergence commenced in May of each experiment year (between May 11 and 18), approximately 2 wk after planting corn and cassava. At this time, emergence had reached 20% in 1994 and 1997 (Figures 1a and 1b) and more than 51% in 1998 (Figure 1c). At the onset of recording data, emergence was 11% in 1999 and 2000 (Figures 1d and 1e). By June of each experiment year, more than 50% of the seedlings had emerged, except in 1998 when 50% emergence occurred in May. Except in 1998, 50% emergence occurred within 6 wk after planting crops. Zimdahl et al. (1988) reported a similar trend in upland rice weed species. Overall, 50% emergence at Ibadan occurred at < 80 θ_{HT}. The only exception was in 1998 when 50% emergence was reached at 99 θ_{HT}. At Umudike, emergence started earlier than in the other locations and reached 70% within 6 wk after planting corn at 78 θ_{HT} (Figures 1g–j). This may be attributed to early rains in the region compared with the drier region at Ibadan.

The rate of emergence at Los Banos possibly was affected by the tillage operations at this site, which would have buried ageratum seeds deeper than those in Nigeria (Figure 1f). The experimental site in Los Banos was rototilled, whereas Ibadan and Umudike had minimum soil tillage with hand hoes.

Emergence Monitoring Technique

At Umudike, there were no differences among methods of measuring and analyzing shoot emergence (Table 1). If monitoring technique were important, the greatest difference probably would have been expected to be between "counting and removing" seedlings and "counting and tagging" seedlings (i.e., leaving seedlings intact). However, average dates to reach 50% emergence in these two treatments were almost identical, April 21 and April 24, respectively.

Model

The parameters of the fitted Weibull function that described the emergence of tropic ageratum as a function of hydrothermal time were $k = 0.0054$ ($a = 38.65$), $c = 1.43$,

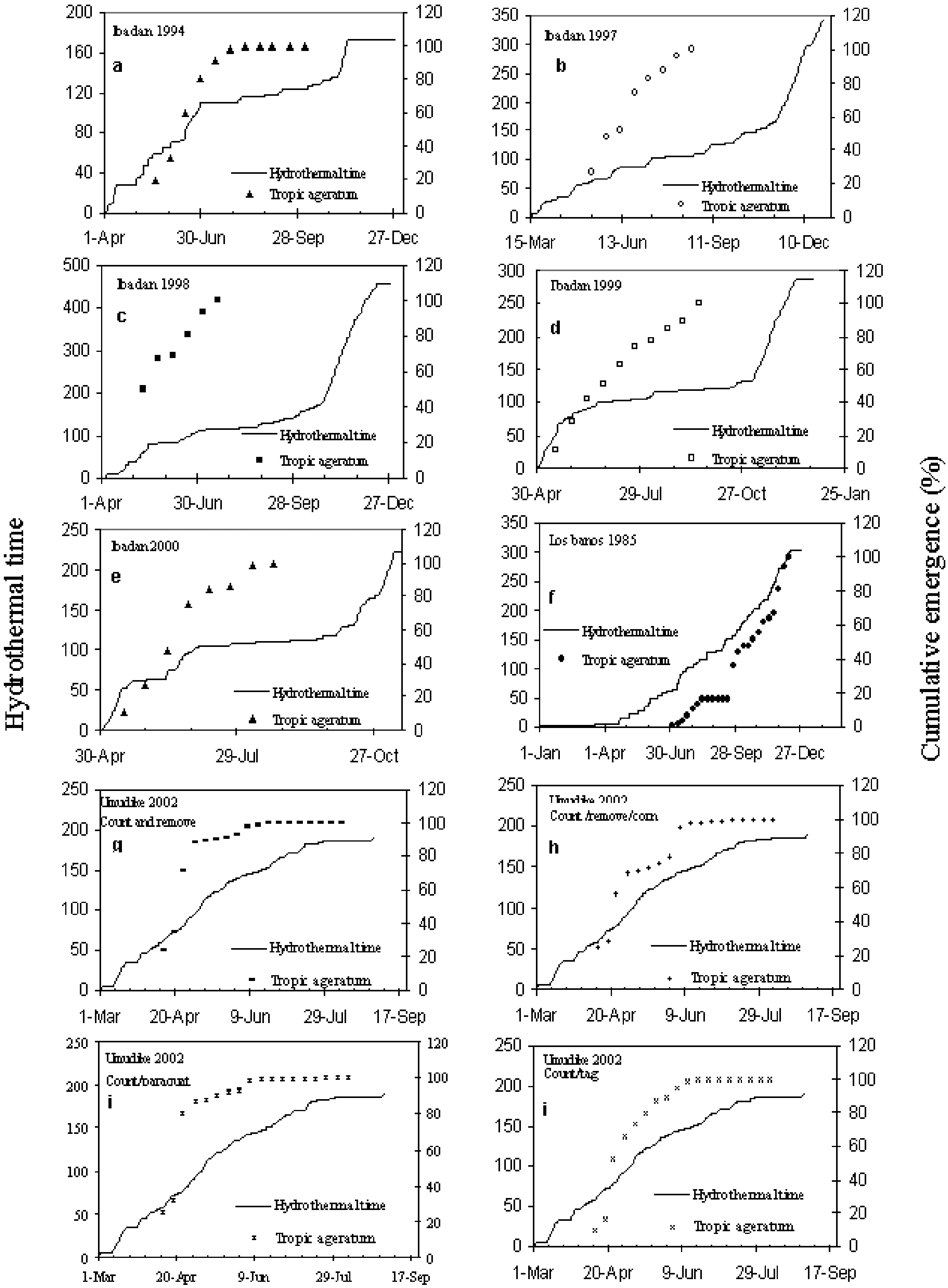

FIGURE 1. Calculated hydrothermal time at 2-cm soil depth and observed percentage of cumulative seedling emergence of tropic ageratum at Ibadan, Nigeria (a–e); Los Banos, Philippines (f); and Umudike, Nigeria (g–j).

TABLE 1. Mean dates of 50 and 90% cumulative percentage of emergence of tropic ageratum seedlings at Umudike in 2002.

Treatment	Time of emergence 50%	90%
	d of year	
Count shoots and tag	114	145
Count shoots and spray paraquat	110	136
Count shoots and remove	111	128
Count shoots and remove in corn	123	145
LSD (0.05)	19	40

and $z = 45$. The cumulative emergence curve predicted by the model (Figure 2a) matched observed seedling emergence closely ($r^2 = 0.83$, P = 0.001, $n = 43$). No emergence was predicted at hydrothermal time periods before 45 θ_{HT}, which is consistent with field emergence starting at 50 θ_{HT}. This suggests that emergence started only when soil moisture was not limiting for 50 degree days, which can be a relatively long period of time, even in a tropical environment, given that the base temperature for tropic ageratum was 28 C. The importance of high water potentials for germination is known for many temperate species (Bradford 2002). Fifty percent seedling emergence predicted by the model at 75 θ_{HT} was similar to what was observed in the field. Seedling emergence increased steadily with increased hydrothermal time until 100 θ_{HT} when more than 80% emergence occurred. Emergence of new seedlings declined after 100 θ_{HT}.

The level and pattern of deviations of model predictions from observations is shown in Figure 2b. In four of the 5 yr of data, no obvious structure was apparent for deviations, which suggests the lack of systematic errors in model predictions. For the year 1999, however, a clear trend of declining levels of deviation occurred between 30 and 60% observed emergence (i.e., predicted emergence always was higher than observed emergence). Maintenance of the 1999 data within the model was assumed to increase the model's robustness, despite our inability to explain the existence of deviation structure during 1999 and its absence in other years.

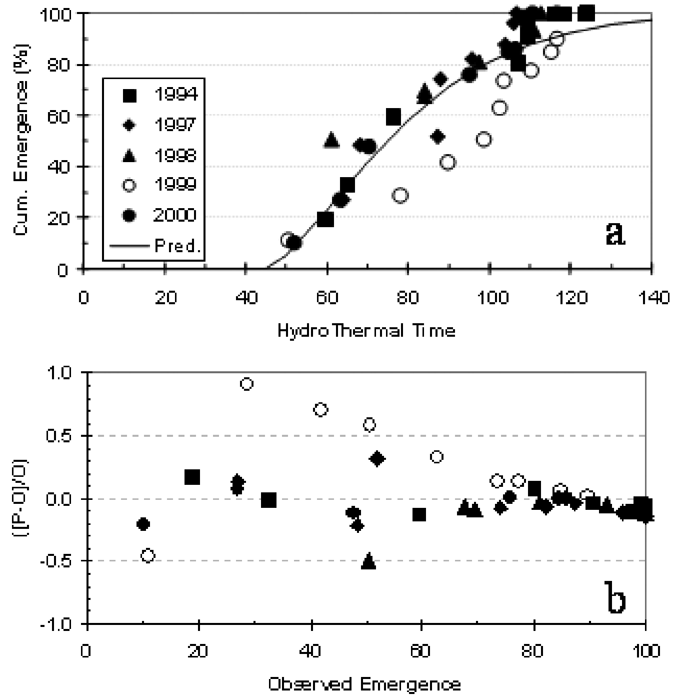

FIGURE 2. (a) The distribution of tropic ageratum seedling emergence (Y) in hydrothermal time (θ_{HT}) fitted to a Weibull function of the form $Y = 100(1 - \exp[-0.0054(\theta_{HT} - 45)^{1.4268}]$. Emergence data were derived from an International Institute of Tropical Agriculture field site in Ibadan, Nigeria, for 5 yr. (b) Relative level and pattern of deviations of predictions (P) and observations (O) shown in Figure 2a.

Model Evaluation

The model was evaluated by comparing percentage of cumulative emergence values from Umudike (southeastern, Nigeria) and Los Banos (Philippines) with the predicted values (Figure 3). RMSE was the tool used to make the comparisons.

At Umudike, the model usually predicted the emergence of ageratum in all the treatments adequately (RMSE $\leq$ 10.1; $n = 18$). RMSE values were low to moderate compared with results of emergence models for other species (e.g., Roman et al. 2000). Overall, the presence of corn (Figure 3c), or intraspecific competition (Figure 3d) where ageratum seedlings were not removed after counting, slowed emergence timing and increased RMSE compared with treatments where seedlings were removed or killed in the absence of corn (Figures 3a and 3b). For example, field seedling emergence in the former two treatments at 100 θ_{HT} was 65% compared with more than 80% in the treatments where ageratum seedlings were either pulled or sprayed with paraquat after counting. Where competition occurred (Figures 3c and 3d), a better fit to the model arose if the lag parameter, z, was altered to 5 or 10. This lag parameter represented elapsed hydrothermal time between initial soil tillage and the first visible presence of seedlings. Thus, it included the time required for seed germination as well as hypocotyl elongation until the cotyledons emerged from the soil surface. Why the lag interval may have been shorter in situations where competing plants were present compared with situations where seedlings were removed physically or chemically is not known. Roman et al. (2000) reported a similar trend in the emergence of common lambsquarters (*Chenopodium album* L.) in corn and attributed this to late closure of the corn canopy.

At Los Banos (Figure 3e), predicted seedling emergence closely matched observed field emergence (RMSE = 8.9; $n = 24$). Small discrepancies between predicted and observed emergence occurred, especially during early and late phases of emergence, but otherwise, the model predictions matched observations remarkably well. Whatever discrepancies occurred may be attributed to tillage effects rather than to soil type because the model was able to predict very closely emergence on sandy clay soil (Figures 3a–d), although it was developed with information from a sandy loam soil. Several studies have shown that tillage can influence weed seed distribution in the soil, soil temperature, soil moisture, and soil structure (Addae et al. 1991; Buhler 1992; Mahli and O'Sullivan 1990; Munkholm et al. 2003). The SHAW model took account of the effects of soil temperature and soil moisture, but the indirect effects of tillage on ageratum emergence through changes in soil structure and seed distribution with soil depth are unknown. The deeper and

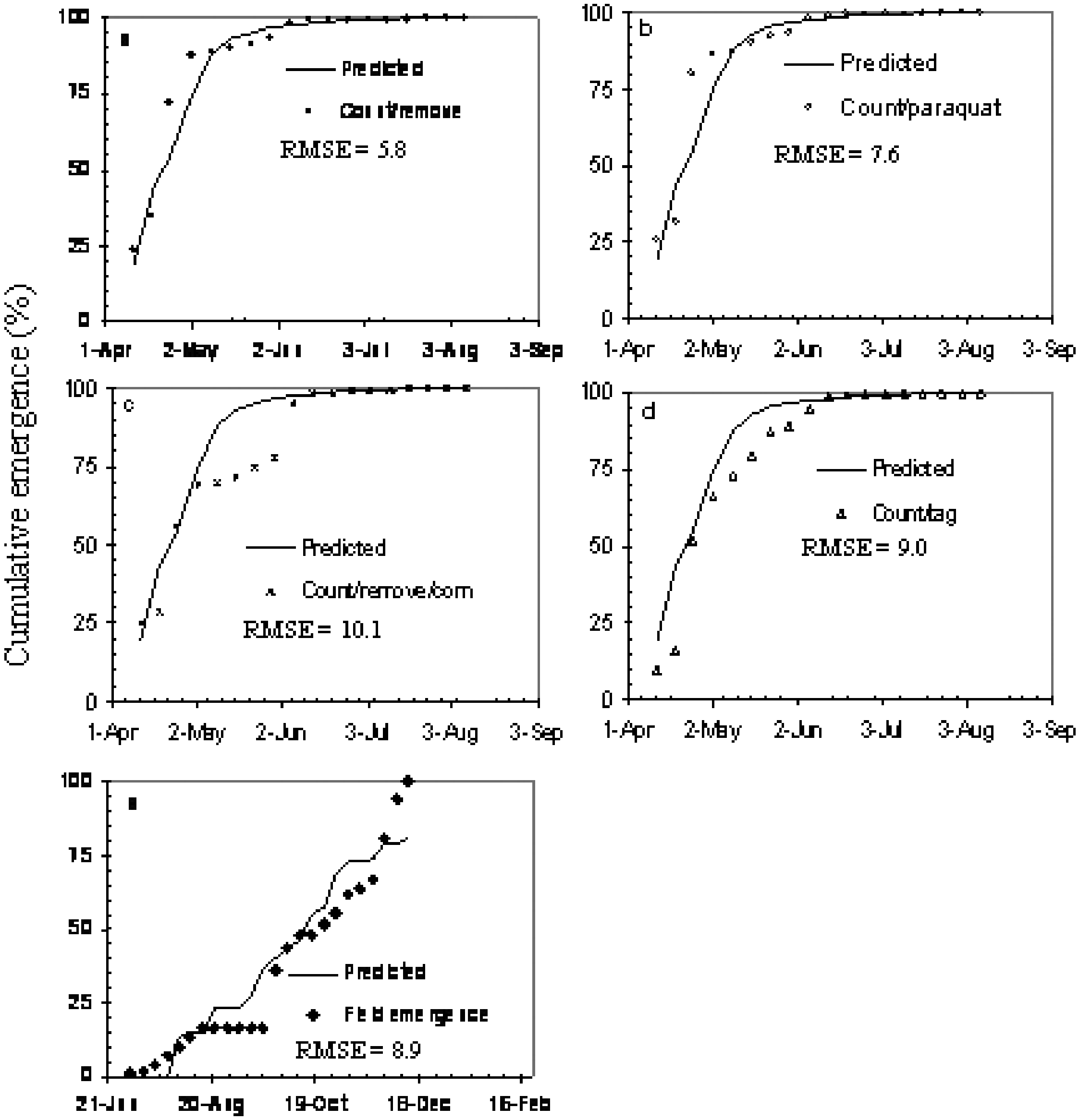

FIGURE 3. Predicted (—) and observed (●, ○, *, △, ■) tropic ageratum seedling emergence at Umudike, Nigeria, where (a) seedlings counted and pulled, (b) seedlings counted and sprayed with paraquat, (c) seedlings counted and removed in corn, (d) seedlings counted, tagged, and allowed to compete, and (e) at Los Banos, Philippines. RMSE represents root mean square error.

more thorough tillage operations in Los Banos, compared with Ibadan, would have been expected to place at least some seeds deeper in the soil and others very near the soil surface, cf. "ploughing" reported by Cousens and Moss (1990) and "spading" reported by Mead et al. (1998). In contrast, minimal tillage at Ibadan and Umudike may have concentrated seeds in a relatively narrow band just below the soil surface, cf. "spring tine" of Mead et al. (1998). Finally, biotypic differences between Nigerian and Philippine populations of tropic ageratum also may be responsible for the small disparities between the predictions and observations in Los Banos.

In summary, a predictive model of tropic ageratum seedling emergence was developed. The model was based on field observations in one location in Nigeria, and it adequately estimated emergence at an independent second location. The model also predicted emergence at a site in the Philippines unexpectedly well, considering the potential differences in biology and known differences in soils and management between the Nigerian and Philippine sites. The integrating factor within the model that allowed comparisons across highly dispersed geographical locations was soil hydrothermal time, which was simulated through a soil physical model. Even if the soil physical model was inaccurate for simulating tropical soil microclimatic conditions, it still provided an objective and consistent index of soil microclimate across sites and years. Accordingly, the emergence model and associated soil physical model may be most useful in tropical locations where conditions approximate those in Nigeria but also applicable in other regions. With such models, extension personnel working on tropical soils may be able to provide additional advice to farmers on the appropriate time for the management of tropic ageratum.

Sources of Materials

[1] Microclimatic data. College of Engineering and Agricultural Technology, University of the Philippines at Los Banos, Los Banos, Laguna, Philippines.

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