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Predicting Emergence of 23 Summer Annual Weed Species

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First- and second-year seedbank emergence of 23 summer annual weed species common to U.S. corn production systems was studied. Field experiments were conducted between 1996 and 1999 at the Iowa State University Johnson Farm in Story County, Iowa. In the fall of 1996 and again in 1997, 1,000 seeds for most species were planted in plastic crates. Seedling emergence was counted weekly for a 2-yr period following seed burial (starting in early spring). Soil temperature at 2 cm depth was estimated using soil temperature and moisture model software (STM^2). The Weibull function was fit to cumulative emergence (%) on cumulative thermal time (TT), hydrothermal time (HTT), and day of year (DOY). To identify optimum base temperature (T_{base}) and base matric potential (ψ_{base}) for calculating TT or HTT, T_{base} and ψ_{base} values ranging from 2 to 17 C and −33 to −1,500 kPa, respectively, were evaluated for each species. The search for the optimal model for each species was based on the Akaike's Information Criterion (AIC), whereas an extra penalty cost was added to HTT models. In general, fewer seedlings emerged during the first year of the first experimental run (approximately 18% across all species) than during the second experimental run (approximately 30%). However, second-year seedbank emergence was similar for both experimental runs (approximately 6%). Environmental effects may be the cause of differences in total seedling emergence among years. Based on the AIC criterion, for 17 species, the best fit of the model occurred using T_{base} ranging from 2 to 15 C with four species also responding to $\psi_{base} = -750$ kPa. For six species, a simple model using DOY resulted in the best fit. Adding penalty costs to AIC calculation allowed us to compare TT and HTT when both models behaved similarly. Using a constant T_{base}, species were plotted and classified as early-, middle-, and late-emerging species, resulting in a practical tool for forecasting time of emergence. The results of this research provide robust information on the prediction of the time of summer annual weed emergence, which can be used to schedule weed and crop management.

Key words: AIC criterion, information-theoretic model comparison approach, thermal time, weather data, Weibull model.

Summer annual weeds typically germinate between spring and early summer, grow throughout the summer, and set seeds by fall (Radosevish et al. 1997). Summer annual weeds are a persistent problem in summer annual row crops, competing directly for water, light, and nutrients, causing yield losses in quantity and quality (Lindquist et al. 1996; Vangessel and Renner 1990). Unlike other pest problems (i.e., insects, diseases), these weeds usually occur in multi-species complexes on an annual basis, with different species having unique biological and ecological characteristics.

Although agriculture is increasingly relying on modern technology, knowledge of the biological systems in which these technologies are used is still critical for implementation of management strategies. Biological information about weeds is valuable and necessary for developing management strategies to minimize their impact (Ogg and Dawson 1984). Scouting fields for pest problems is essential in any cropping system and knowledge of the timing and sequence of weed species emergence could increase the effectiveness of weed scouting trips and subsequent management practices. Producers with cropping systems that use little to no herbicides need information on weed emergence to plan cultural practices (e.g., tillage, planting time, crop choice to effectively compete with weeds), and those relying on chemical strategies need this information to plan the best time for a herbicide application (Anderson 1994; Buhler et al. 1997).

The success of any annual plant is directly correlated to its time of seedling emergence because it determines the ability of a plant to compete with its neighbors, survive biotic and abiotic stresses, and reproduce (Forcella et al. 2000). For some species, emergence occurs over a short period of time (i.e., few weeks), but for others it can occur over longer

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periods (i.e., months) (Ogg and Dawson 1984). According to Davis et al. (2008), if all weed seeds were to germinate and emerge at the same time, weed management would be a simple task. Instead, weeds are an annual problem because they germinate at different times, allowing them to escape control, produce seed, and create soil seedbanks that may persist for several years (Burnside et al. 1996; Conn et al. 2006).

Most newly produced seeds germinate within the first year after burial. However, some seeds of many species remain viable in the seedbank for years (Baskin and Baskin 1988). The period and pattern of emergence of the weed community depend on the species present in the seedbank and their interaction with the environment (Forcella et al. 1997; Stoller and Wax 1973). Therefore, knowledge of the weed species present in the soil seedbank and when these species are most likely to emerge is important in planning effective weed control programs (Buhler et al. 1997; Forcella et al. 2000).

Summer annual weed species are known to present similar emergence patterns across years within a geographical location (Baskin and Baskin 1988; Hartzler et al. 1999; Stoller and Wax 1973). Temperature has been reported to be the main environmental factor regulating germination and emergence of weed species (Baskin and Baskin 1988). Scientists have developed TT models to predict emergence of weed species based on daily accumulation of heat units or growing degree days (GDD) above a minimum base threshold value (T_{base}). The predictive models for weed emergence based on accumulation of TT appear to be accurate enough for projections of weed emergence time (Grundy 2003). Moreover, soil temperature data are easily accessible, making this type of model practical and useful to farmers. Because water is also an essential component for seed germination, Gummerson (1986) proposed the HTT concept, accounting for the effects of soil water content on time of seedling emergence. HTT models only allow the accumulation of heat units when soil moisture is above a threshold soil water content required for seed germination (Ψ_{base}). HTT models have improved the accuracy of TT model predictions, particularly in locations where water is limiting during the emergence period (Leguizamon et al. 2005). Because TT and HTT models are developed based on environmental conditions, they can be used to predict weed emergence across different years and geographical regions. The objectives of this research were to evaluate and develop predictive models of emergence of 23 common summer annual weed species based on their first- and second-year seedbank emergence after initial burial.

Materials and Methods

Seed Collection and Preparation. Individual lots of mature weed seeds of 23 species (Table 1) were collected at multiple sites and times in central Iowa throughout late summer and fall of 1996 and again in 1997 (for the experiments established during fall of 1996 and 1997, respectively). Seeds were collected in corn and soybean fields in Story County, Boone County, and Webster County, Iowa. As many seed heads as possible of mature plants in each sampled field were placed into a bag and lightly tapped to collect mature seeds. Once enough seeds were collected for each species, the seeds from the different fields were blended together and cleaned, generating seed lots representative of a range of locations. A set of 20-cm-diam sieves with 7-mesh screens and 10-mesh screens (specified sieving opening of 2.83 mm and 2.0 mm, respectively) were used to separate larger debris and chaff, and a seed blower was used to separate the finer hulls, small chaff, and smaller and lighter seeds. Cleaned samples were then spread out on large metal trays and immature seeds, insect-damaged seeds, and seeds from other species were manually removed. Once pure samples were prepared, 1,000 seeds per species were counted by a seed counter and placed in paper envelopes that were stored dry at room temperature until establishment (approximately 1 mo). This procedure was used for all species but common cocklebur (*Xanthium strumarium* L.), field sandbur (*Cenchrus spinifex* Cav.), and burcucumber (*Sicyos angulatus* L.), which had 50 burs, 1,000 burs, and 150 seeds, respectively, manually cleaned and counted, and then placed in paper envelopes.

Field Experiments. Field experiments were conducted to evaluate first- and second-year seedbank emergence characteristics of each species. Field experiments were conducted between 1996 and 1999 at the Iowa State University Johnson Farm (41.98°N, 93.64°W) in Story County, Iowa. The soil was a Clarion loam (46.8% sand, 39.6% silt, and 13.6% clay) with 4.6% organic matter and pH of 6.7.

To minimize the herbicide residual and seedbank effect of weed species commonly found in cropped fields, the studies were located in an area that had been in turf grass for many years. The turf grass area

Table 1. Weed species included in this study and their respective base temperature (T_{base}) values reported in the literature.[a]

Common name	Latin name	Family	T_{base} (C)	Citation
Redroot pigweed	*Amaranthus retroflexus* L.	Amaranthaceae	12.1	Masin et al. 2010
Common waterhemp	*Amaranthus rudis* Sauer	Amaranthaceae	10.0	Leon et al. 2004
Common ragweed	*Ambrosia artemisiifolia* L.	Asteraceae	3.6	Shrestha et al. 1999
Giant ragweed	*Ambrosia trifida* L.	Asteraceae	2.0	Abul-Fatih and Bazzaz 1979
Common sunflower	*Helianthus annuus* L.	Asteraceae	4.4	Clay et al. 2014
Common cocklebur	*Xanthium strumarium* L.	Asteraceae	17.0	Norsworthy and Oliveira 2007
Common lambsquarters	*Chenopodium album* L.	Chenopodiaceae	4.2	Roman et al. 1999
Kochia	*Kochia scoparia* (L.) Schrad.	Chenopodiaceae	3.5	Al-Ahmadi and Kafi 2007
Ivyleaf morningglory	*Ipomoea hederacea* Jacq.	Convolvulaceae	10	Alm et al. 1993
Burcucumber	*Sicyos angulatus* L.	Cucurbitaceae	> 10.0	Mann et al. 1981
Velvetleaf	*Abutilon theophrasti* Medik.	Malvaceae	8.0	Leon et al. 2004
Venice mallow	*Hibiscus trionum* L.	Malvaceae	> 10.0	Chachalis et al. 2008
Field sandbur	*Cenchrus spinifex* Cav.	Poaceae	NA	—
Barnyardgrass	*Echinochloa crus-galli* (L.) Beauv.	Poaceae	11.7	Masin et al. 2010
Woolly cupgrass	*Eriochloa villosa* (Thunb.) Kunth	Poaceae	> 10.0	Bello et al. 2000
Fall panicum	*Panicum dichotomiflorum* Michx.	Poaceae	NA	—
Giant foxtail	*Setaria faberi* Herrm.	Poaceae	14.0	Leon et al. 2004
Yellow foxtail	*Setaria pumila* (Poir.) Roemer & J.A. Schultes	Poaceae	10.4	Masin et al. 2010
Green foxtail	*Setaria viridis* (L.) Beauv.	Poaceae	12.5	Masin et al. 2010
Shattercane	*Sorghum bicolor* (L.) Moench ssp. *arundinaceum* (Desv.) de Wet & Harlan	Poaceae	NA	—
Pennsylvania smartweed	*Polygonum pensylvanicum* L.	Polygonaceae	NA	—
Jimsonweed	*Datura stramonium* L.	Solanaceae	10.5	Pawlak et al. 1990
Eastern black nightshade	*Solanum ptychanthum* Dunal	Solanaceae	10.9	Weaver et al. 1988

[a] NA represents undetected values published in the literature.

used in this study was part of the yard of the main building at the Johnson Farm where there were no reports of grain crops planted in the past. The presence of the weed species evaluated in this study was not observed in the area where the studies were established (data not shown). In July of 1996 the turf was sprayed with a 3% solution of glyphosate and in September the plot area was then rototilled to a depth of 20 cm. Before the study was installed in November, the soil was rototilled again to smooth the surface and to help facilitate installation of the experimental units. The same procedures were repeated in an adjacent area in 1997 to replicate the experiment over years.

A randomized complete block design with three replications and 23 species was used, where each experimental unit contained seeds of a single species. Experimental units were composed of 20- by 20-cm plastic crates with 15 cm height in 1996, and polyvinylchloride (PVC) cylinders with 30 cm diam and 15 cm height in 1997. After the area was rototilled the second time, the experimental units (crates or PVC pipes) were laid out 1 m apart and then pushed into the soil. A 1-cm lip of the frame was left above the soil surface to keep the seeds in the experimental area. On November 5, 1996, and November 7, 1997, seeds of each species were buried by removing the upper 5 cm of soil within a plastic crate or PVC cylinder, placing it in a bucket, adding a packet of seeds, mixing seeds with the soil, and then returning the soil to the frame and gently packing it by hand. Soybeans [*Glycine max* (L.) Merr.] were planted by hand at a 3-cm depth in rows spaced 0.6 m apart between experimental units to create a crop canopy on May 15, 1997, and May 21, 1998, for the experiment established in 1996 and on May 21, 1998, and May 13, 1999, for the experiment established in 1997.

Data Collection. Emerged seedlings were counted weekly for a 2-yr period following seed burial for all experimental units. To evaluate first- and second-year seedbank emergence for the experiment established in the fall of 1996, counts were conducted from April through October in 1997 and similarly in 1998. Counts for the experiment established in 1997 were conducted from March through October in 1998 and from April through September in 1999. Emerged seedlings were counted and removed until no additional emergence was observed in each year. Grass species were pulled and discarded when they reached a height of 1 cm, whereas broadleaf species were pulled and discarded when the cotyledons were fully expanded. This procedure was deemed to be the most efficient way to accurately identify and remove the emerged seedlings while disturbing the soil as little as possible. Daily maximum and minimum air temperature and daily precipitation were obtained from the nearest automated weather station located in Ames, IA (Iowa Environmental Mesonet, Iowa State University Department of Agronomy; site ID: A130209; 42.02°N, 93.77°W), at approximately 11.0 km northwest of the Iowa State University Johnson Farm. Soil temperature and moisture model software (STM^2) (Spokas and Forcella 2009) was then used to predict daily soil temperature (C) and moisture (kPa) at a 2-cm depth based on daily maximum and minimum air temperature, daily precipitation, along with soil properties (sand, silt, clay, and organic matter content), latitude, longitude, and elevation (302 m) of the research site.

Modeling Procedures. Emergence data were converted from weekly counts to cumulative emergence (%) based on the total seedling emergence per experimental unit per year. Cumulative soil HTT was calculated on a daily basis starting at January 1 for each year (Gummerson 1986):

$$\mathrm{HTT} = \sum\nolimits_{i=1}^{n} \left[(\mathrm{T} \times \psi) \times (\mathrm{T}_{\mathrm{mean}} - \mathrm{T}_{\mathrm{base}})\right] \quad [1]$$

where T (thermal portion of the equation) is interpreted as $\mathrm{T}_{\mathrm{mean}} > \mathrm{T}_{\mathrm{base}} = 1$, otherwise $= 0$; Ψ (hydro portion of the equation) as $\Psi > \Psi_{\mathrm{base}} = 1$, otherwise $= 0$. $\mathrm{T}_{\mathrm{mean}}$ is the average daily soil temperature at a 2-cm depth (C), $\mathrm{T}_{\mathrm{base}}$ is the minimum temperature threshold for seed germination (C), Ψ is daily mean matric potential (kPa) at a 2-cm depth, Ψ_{base} is base matric potential required for seedling emergence (kPa), *i* is the starting date to accumulate TT (January 1), and *n* is the number of days after *i*. $\mathrm{T}_{\mathrm{mean}} - \mathrm{T}_{\mathrm{base}}$ heat units are accumulated on a daily basis when T and ψ are adequate for germination. As our $\mathrm{T}_{\mathrm{base}}$, 16 candidate threshold values ranging from 2 C to 17 C at 1 C intervals were tested. These values were chosen because $\mathrm{T}_{\mathrm{base}}$ values for summer annual weeds as low as 2 C and as high as 17 C have been reported (Abul-Fatih and Bazzaz 1979; Norsworthy and Oliveira 2007). As our Ψ_{base}, four candidate threshold values were tested: -33 (field capacity), -750, $-1{,}500$ (permanent wilting point for plants), and $-\infty$ (equivalent to TT model where ψ is not included) kPa. These values were chosen because they represent a range of soil moisture

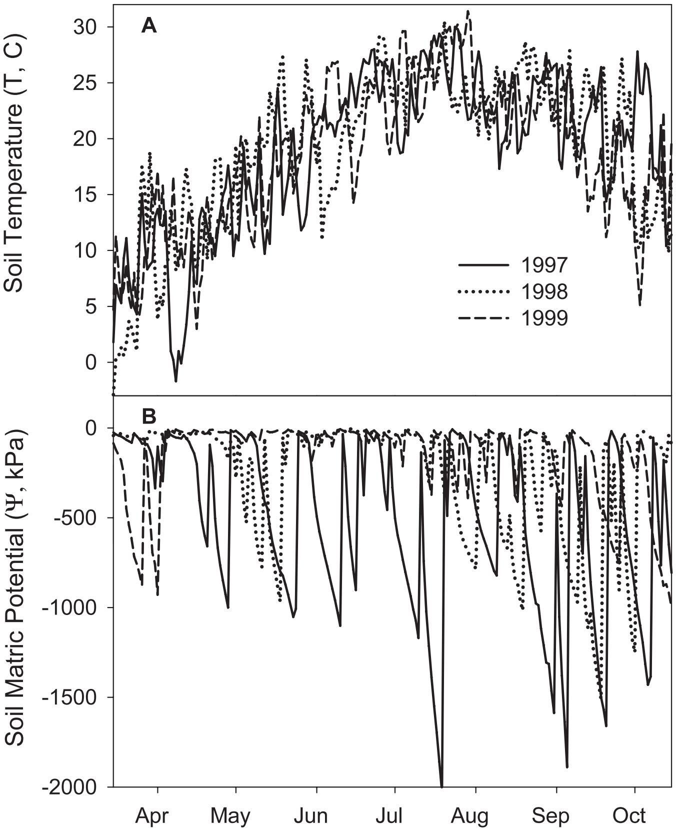

Figure 1. Daily (A) soil temperature (T, C) and (B) matric potential (ψ, kPa) at 2-cm depth estimated by soil temperature and moisture model software (STM^2) during the weed emergence study.

conditions observed during this study (from wet [−33 kPa] to a drier condition [−1,500 kPa]). Moreover, Ψ rarely dropped below −1,500 kPa during the time weeds were actively emerging (Figure 1).

Fitting the Models. The cumulative emergence of each species pooled over years was modeled with the Weibull function in which the independent variables were the 48 permutations of HTT, 16 permutations of TT, and DOY:

$$y = Asym \times \{1 - \exp[-\exp(lrc) \times (\mathrm{HTT, TT,\ or\ DOY}^{pwr})]\} \qquad [2]$$

where y is cumulative emergence (%), *Asym* is the horizontal asymptote (theoretical maximum for y normalized to 100%), *lrc* is the natural logarithm for the rate of increase, and *pwr* is the power to which HTT, TT, or DOY is raised (Crawley 2007). To assure a smooth and consistent emergence pattern over time and consequent good fit of the models, cumulative emergence data for a specific experimental run–emergence year was only used when at least 1% emergence from the seedbank was observed within a year (10 seedlings experimental $\mathrm{unit}^{-1}\ \mathrm{yr}^{-1}$). This procedure was used for modeling the emergence pattern of all weed species but common cocklebur and burcucumber; for these two species, a minimum of five emerged seedlings within a year was required in order to include the data in the modeling portion of this study. Weibull parameters (*lrc* and *pwr*) for each model were estimated using the *NLME* package of R version 2.15.1 (R Foundation for Statistical Computing, Wien, Austria).

The information-theoretic model comparison approach (AIC), was used as the theoretical basis for model selection (Anderson 2008). AIC relies on the maximum likelihood to estimate the expected distance between the predictive model and the "true generating mechanism" or reality (Anderson 2008). The AICc (corrected AIC) and model probability (AIC*w*) were computed for each model in the pool of candidate models (total of 65 models for each species). AICc was calculated as (Anderson 2008):

$$\mathrm{AICc} = -2\mathrm{LL} + 2\mathrm{K}(n/[n - \mathrm{K} - 1]) \qquad [3]$$

where LL is the log-likelihood function of the model parameters given the data, K is the number of parameters estimated for the model, and *n* is the sample size. The LL for each model was obtained using the *logLik* command of R version 2.15.1 (R Foundation). For models using TT and DOY as explanatory variables, a penalty cost of 1 was added to the number of parameters (K = K + 1) when calculating the AICc, and a penalty cost of 2 (K = K + 2) was added for models based on accumulation of HTT. TT and DOY models require a single input (daily temperature and DOY), whereas HTT models are more complex, requiring two inputs (daily soil temperature and moisture). AIC*w* was calculated as (Anderson 2008):

$$\mathrm{AIC}w_i = \left[\exp(-1/2\Delta i) \Big/ \sum_{r=1}^{R} \exp(-1/2\Delta r)\right] \qquad [4]$$

where Δi is the AICc difference between the top model (model with smallest AICc) and the *i*th model. *R* represents the total number of candidate models. The AIC*w* for all models included in the pool of candidates must sum to 1.

The model with the smallest value of AICc and highest probability (AIC*w*) was considered the "top model" or the best descriptor of the full reality given the set of candidate models and the data (Anderson 2008), indicating optimum $\mathrm{T_{base}}$ and ψ_{base} for each

Table 2. Average percentage ± SE of emerged seedlings across experimental runs (total of two) and emergence year (1st and 2nd seedbank emergence year).[a]

	1st Experimental run		2nd Experimental run	
Common name	1st Year (1997)	2nd Year (1998)	1st Year (1998)	2nd Year (1999)
Redroot pigweed	9.7 ± 0.8	6.7 ± 1.2	6.2 ± 0.4	2.7 ± 0.1
Common waterhemp	3.1 ± 0.4	5.1 ± 0.5	9.2 ± 0.9	2.9 ± 1.0
Common ragweed	15.1 ± 0.3	1.4 ± 0.3	22.3 ± 1.9	6.2 ± 0.1
Giant ragweed	30.9 ± 1.3	8.7 ± 1.5	58.2 ± 7.0	8.4 ± 0.9
Common sunflower	18.6 ± 1.3	0.0 ± 0.0	41.2 ± 2.4	7.8 ± 1.0
Common cocklebur	64.7 ± 7.2	11.3 ± 2.0	73.3 ± 1.1	0.0 ± 0.0
Common lambsquarters	5.2 ± 1.5	3.3 ± 1.1	10.7 ± 0.4	7.9 ± 0.7
Kochia	5.8 ± 1.1	0.0 ± 0.0	20.4 ± 3.8	0.4 ± 0.1
Ivyleaf morningglory	8.1 ± 0.7	29.4 ± 2.4	11.5 ± 0.4	12.2 ± 1.8
Burcucumber	6.0 ± 0.3	6.2 ± 1.1	6.2 ± 0.9	18.2 ± 2.1
Velvetleaf	16.6 ± 2.3	14.5 ± 1.1	33.6 ± 5.0	5.7 ± 0.6
Venice mallow	4.9 ± 0.7	6.6 ± 0.7	6.5 ± 0.2	9.6 ± 0.7
Field sandbur	46.7 ± 2.3	1.1 ± 0.2	93.4 ± 3.5	2.8 ± 0.7
Barnyardgrass	43.5 ± 2.4	3.1 ± 0.8	18.7 ± 3.2	7.6 ± 0.9
Woolly cupgrass	12.7 ± 0.7	0.2 ± 0.0	28.6 ± 3.3	0.4 ± 0.1
Fall panicum	17.9 ± 0.8	0.8 ± 0.5	13.3 ± 1.2	14.8 ± 1.7
Giant foxtail	26.6 ± 2.4	8.4 ± 1.5	40.5 ± 2.2	7.8 ± 0.7
Yellow foxtail	0.2 ± 0.1	0.3 ± 0.1	37.4 ± 6.9	6.6 ± 1.1
Green foxtail	21.8 ± 1.6	3.8 ± 0.6	26.6 ± 3.2	4.2 ± 1.2
Shattercane	6.8 ± 0.6	0.1 ± 0.0	20.3 ± 1.6	0.2 ± 0.2
Pennsylvania smartweed	27.8 ± 1.5	5.2 ± 0.4	51.7 ± 3.8	2.9 ± 0.4
Jimsonweed	0.1 ± 0.1	0.1 ± 0.1	44.6 ± 2.4	4.4 ± 0.2
Eastern black nightshade	10.4 ± 0.6	0.9 ± 0.1	15.9 ± 2.5	3.3 ± 0.9
All species combined	17.5 ± 3.3	5.1 ± 1.4	30.0 ± 4.6	6.0 ± 1.0

[a] First and second experimental runs were established in the fall of 1996 and 1997, respectively, at the Iowa State University Johnson Farm in Story County, Iowa. One thousand seeds were planted in each experimental unit for all species except for common cocklebur, field sandbur, and burcucumber, which had 50 burs, 1,000 burs, and 150 seeds planted, respectively.

weed species. If the top model was based on DOY, then DOY is a better predictor of emergence than accumulation of heat units. Additionally, a "basic model" (using a constant T_{base} across all species) was included in our analysis to effectively compare the sequence of summer annual weed emergence among species.

Model Goodness of Fit. When using the AIC criterion, Anderson (2008) recommends reporting the goodness of fit for the top model. Therefore, root mean square error (RMSE) and modeling efficiency coefficient (ME) of the "top model" and "basic model" were calculated as indicators of goodness of fit for each species. The RMSE was calculated according to Roman et al. (2000):

$$RMSE = \left[1/n \sum_{i=1}^{n} (Pi - Oi)^2\right]^{1/2} \qquad [5]$$

where Pi is the predicted value and Oi the observed value, and n is the total number of comparisons. The smaller the RMSE value, the closer the observed values are to the predicted. The ME, which differs from R^2 only by not having a lower bound, was calculated according to Mayer and Butler (1993):

$$ME = 1 - \left[\sum_{i=1}^{n} (Oi - Pi)^2 \Big/ \sum_{i=1}^{n} (Oi - \bar{O}i)^2\right] \qquad [6]$$

where $\bar{O}i$ is the mean observed value. ME values can range between $-\infty$ and 1, with values closer to 1 indicating more-accurate predictions.

Results and Discussion

Seedbank Emergence. First- and second-year seedbank emergence was species- and year-specific, ranging from less than 1 to 93% and from 0 to 29%, respectively (Table 2). Results indicate that, in general, fewer weeds emerged during the first year of the first experimental run (1997; approximately 18% across all species) than during the second experimental run (1998; approximately 30%). However, second-year seedbank emergence was similar for both experimental runs (1998 and 1999; approximately 6%). In 1997, lower temperatures and precipitation were observed during late winter and spring when compared to the 11-yr average (1986 to 1996) and

Table 3. Average daily minimum and maximum temperature, and cumulative daily precipitation by month at Ames, IA. Eleven-year average temperature and precipitation are included for reference (11-yr avg.; 1986 to 1996).[a]

	Minimum temperature (C)				Maximum temperature (C)				Precipitation (mm)			
Month	1997	1998	1999	11-yr avg.	1997	1998	1999	11-yr avg.	1997	1998	1999	11-yr avg.
January	−13.8	−9.0	−12.2	−10.9	−4.3	−0.9	−4.2	−0.6	12.6	27.5	15.4	13.8
February	−7.8	−2.4	−3.9	−9.3	−0.2	4.1	4.6	0.8	23.4	21.1	10.8	14.5
March	−2.5	−3.4	−2.9	−2.1	9.9	4.1	8.8	9.2	44.4	67.8	20.7	50.5
April	0.9	4.9	4.7	3.0	13.5	15.3	15.0	16.2	78.3	67.6	191.3	88.5
May	7.0	12.5	10.8	10.5	20.2	24.7	21.0	22.6	56.0	96.3	134.1	122.8
June	15.8	14.5	15.8	16.3	28.4	24.5	25.5	27.2	91.1	249.2	171.2	141.0
July	17.4	18.1	19.8	17.9	29.0	28.7	30.6	28.7	94.2	63.5	146.1	162.2
August	15.9	18.2	16.1	16.8	26.8	27.8	26.6	27.9	31.3	80.3	143.5	111.5
September	11.8	13.5	8.9	11.4	25.2	27.4	23.0	23.9	56.8	25.4	53.3	97.6
October	5.9	6.4	3.3	4.6	17.3	17.0	18.0	17.1	12.1	87.6	7.6	51.9
November	−3.8	−0.2	0.0	−3.1	4.1	10.3	13.6	6.7	25.9	16.1	10.2	56.9
December	−5.4	−7.6	−8.5	−8.0	0.5	4.3	3.0	0.4	8.9	6.1	9.9	22.2
Average	3.4	5.5	4.3	3.9	14.2	15.6	15.5	15.0	—	—	—	—
Cumulative	—	—	—	—	—	—	—	—	535.0	808.5	914.1	933.4

[a] Weather data were obtained from an automated weather station in Ames, IA (Iowa Environmental Mesonet, Iowa State University Department of Agronomy; site ID: A130209; 42.02°N, 93.77°W), located approximately 11.0 km northwest of the Iowa State University Johnson Farm.

the 1998 and 1999 research years at Ames, IA (Table 3). The majority of weed seedlings emerged from March through June in this study, and cooler temperatures and less available soil moisture probably reduced total weed emergence in 1997 (Figure 1). Moreover, a different seed lot was used in each experimental run (initial seed viability was not determined in this study). Therefore, environmental effects on seed lot quality and variability in seed viability between lots may be the cause of differences in total seedling emergence among years (Tables 2 and 3; Figure 1).

For kochia [*Kochia scoparia* (L.) Schrad.], woolly cupgrass [*Eriochloa villosa* (Thunb.) Kunth], and shattercane [*Sorghum bicolor* (L.) Moench ssp. *arundinaceum* (Desv.) de Wet & Harlan], second-year emergence was very low for both experimental runs (Table 2). Schwinghamer and Van Acker (2008) reported the majority of kochia seedlings germinating within the first spring following burial and ungerminated seeds not being persistent in the seedbank. Buhler and Hartzler (2001) reported woolly cupgrass having short seedbank persistence. These results indicate that persistence of these species in the seedbank may not be very long and future infestations may depend upon continuous seed rain events. Therefore, preventing seed production might be an adequate management strategy to reduce these species' infestations in following cropping seasons (Schwinghamer and Van Acker 2008). For unknown reasons, yellow foxtail [*Setaria pumila* (Poir.) Roemer & J.A. Schultes] and jimsonweed (*Datura stramonium* L.) emergence during both years of the first experimental run was very low ($< 0.5\%$). However, in the second experimental run, greater emergence was observed for both species during the first year ($> 37\%$) than in the second ($> 4\%$; similar pattern of most species included in this study).

First-year emergence was greater than second-year emergence for the majority of species included in this study (Table 2). This is an indication that most viable seeds will germinate when environmental conditions become favorable for emergence within a few months following burial. However, a proportion of seeds may remain dormant or quiescent in the seedbank and germinate during subsequent growing seasons. Seeds of most summer annual weeds are dormant at maturity, but dormancy is usually overcome after exposure to low temperatures during winter (Baskin and Baskin 1988). Moreover, high summer temperatures tend to lead ungerminated seeds of early-season emerging species to reenter dormancy, but not late-emerging species (Baskin and Baskin 1988). However, viable seeds of both groups are unlikely to germinate during fall because of low temperatures.

Estimation of T_{base} and Ψ_{base} and Their Importance for Each Species. Based on the AIC criterion, for 13 species the best fit of the model occurred when using TT models with T_{base} ranging from 2 to 15 C (Table 4). For four species (common sunflower [*Helianthus annuus* L.], kochia, burcu-

Table 4. Optimum T_{base} and ψ_{base} according to Akaike's Information Criterion, Weibull model parameters (*lrc* and *pwr*), and the top model's goodness of fit (RMSE and ME) for each species.[a,b]

Common name	T_{base} (C)	ψ_{base} (kPa)	*lrc*	*pwr*	RMSE	ME
Redroot pigweed	ni	ni	−41.5222	8.0555	7.92	0.97
Common waterhemp	ni	ni	−45.7327	8.9039	10.51	0.94
Common ragweed	13.0	ni	−5.5039	1.7411	9.11	0.91
Giant ragweed	13.0	ni	−3.4693	1.2593	9.88	0.82
Common sunflower	12.0	−750	−9.5447	2.4253	6.09	0.97
Common cocklebur	10.0	ni	−7.4560	1.2830	8.21	0.96
Common lambsquarters	7.0	ni	−5.9983	1.0351	11.24	0.87
Kochia	12.0	−750	−3.2025	1.2094	4.43	0.94
Ivyleaf morningglory	ni	ni	−33.4953	6.3794	10.15	0.94
Burcucumber	4.0	−750	−12.3528	2.0033	14.55	0.83
Velvetleaf	8.0	ni	−11.4287	1.9906	8.69	0.95
Venice mallow	9.0	ni	−15.8153	2.5837	9.21	0.95
Field sandbur	ni	ni	−51.6421	10.3587	12.99	0.90
Barnyardgrass	5.0	ni	−17.9508	2.8557	7.28	0.97
Woolly cupgrass	15.0	ni	−5.6945	1.4344	5.21	0.98
Fall panicum	7.0	−750	−15.6982	2.5200	7.15	0.97
Giant foxtail	2.0	ni	−18.6439	2.8058	7.18	0.97
Yellow foxtail	2.0	ni	−28.0453	4.2447	5.33	0.98
Green foxtail	9.0	ni	−11.1596	1.8738	6.33	0.98
Shattercane	14.0	ni	−7.3347	1.4881	3.75	0.99
Pennsylvania smartweed	11.0	ni	−9.8950	2.3720	9.13	0.92
Jimsonweed	ni	ni	−101.371	20.887	5.19	0.98
Eastern black nightshade	ni	ni	−39.421	7.849	14.85	0.87

[a] Abbreviations: T_{base}, base temperature; ψ_{base}, base matric potential; *lrc*, the natural logarithm for the rate of increase; *pwr*, the power to which the explanatory variable (accumulated hydrothermal time, accumulated thermal time, or day of year) is raised; RMSE, root mean square error; ME, modeling efficiency coefficient; ni, according to the Akaike's Information Criterion, the specific environmental soil parameter was not important on improving model accuracy.

[b] For redroot pigweed, common waterhemp, ivyleaf morningglory, field sandbur, jimsonweed, and eastern black nightshade the model using day of year as explanatory variable had the best fit to the data.

cumber, and fall panicum [*Panicum dichotomiflorum* Michx.]), a HTT using $\psi_{base} = -750$ kPa and T_{base} ranging from 4 to 12 C resulted in the best fit. For six species—redroot pigweed (*Amaranthus retroflexus* L.), common waterhemp (*Amaranthus rudis* Sauer), ivyleaf morningglory (*Ipomoea hederacea* Jacq.), field sandbur, jimsonweed, and eastern black nightshade (*Solanum ptychanthum* Dunal)—a simple model using DOY as the explanatory variable resulted in the best fit. This indicates that for these species there might be some factors driving emergence other than daily average soil temperature and moisture. Leon et al. (2004) reported that common waterhemp required a minimum temperature fluctuation to reduce the proportion of dormant seeds in the population and suggested that temperature fluctuation should be included in predictive models for this species. For 11 species—common ragweed (*Ambrosia artemisiifolia* L.), giant ragweed (*Ambrosia trifida* L.), velvetleaf (*Abutilon theophrasti* Medik.), Venice mallow (*Hibiscus trionum* L.), barnyardgrass [*Echinochloa crus-galli* (L.) Beauv.], woolly cupgrass, giant foxtail (*Setaria faberi* Herrm.), yellow foxtail, green foxtail [*Setaria viridis* (L.) Beauv.], shattercane, and Pennsylvania smartweed (*Polygonum pensylvanicum* L.)—TT and HTT (using a $\psi_{base} = -1{,}500$ kPa) models showed similar performance (same log-likelihood). However, when the extra penalty cost for the hydro portion of the HTT model was taken into account on AICc calculation (Equation 3), TT models yielded better performance than HTT models (Figure 2). This may be because Ψ rarely dropped below −1,500 kPa during the time when most weeds were emerging (Figure 1); thus, accumulation of heat units was similar between TT and HTT ($\psi_{base} = -1{,}500$ kPa) models.

The addition of a penalty cost for the hydro portion of our models when comparing the fit of TT to HTT has not been previously reported. Without a proper penalty cost, more complex models tend to perform better; however, the more complex the model, the greater the "noise" (noninformation) included in it (Anderson 2008). Therefore, the principle of parsimony, or trade-off between underfitting vs. overfitting, must be considered. Furthermore, this approach allows

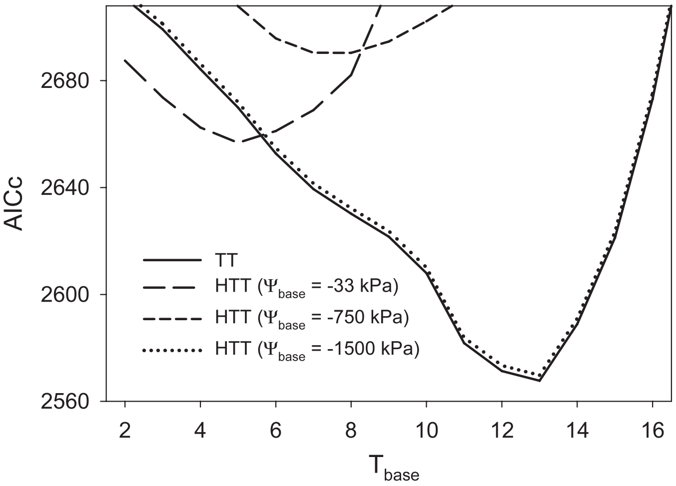

Figure 2. Corrected Akaike's Information Criterion (AICc) of predictive models for giant ragweed emergence based on cumulative thermal time (TT) and hydrothermal time (HTT) (base matric potential [ψ_{base}] = −33, −750, and −1,500 kPa) with base temperature (T_{base}) ranging from 2 to 17 C. As reference, AICc for the model using day of year as explanatory variable was equal to 2,789.

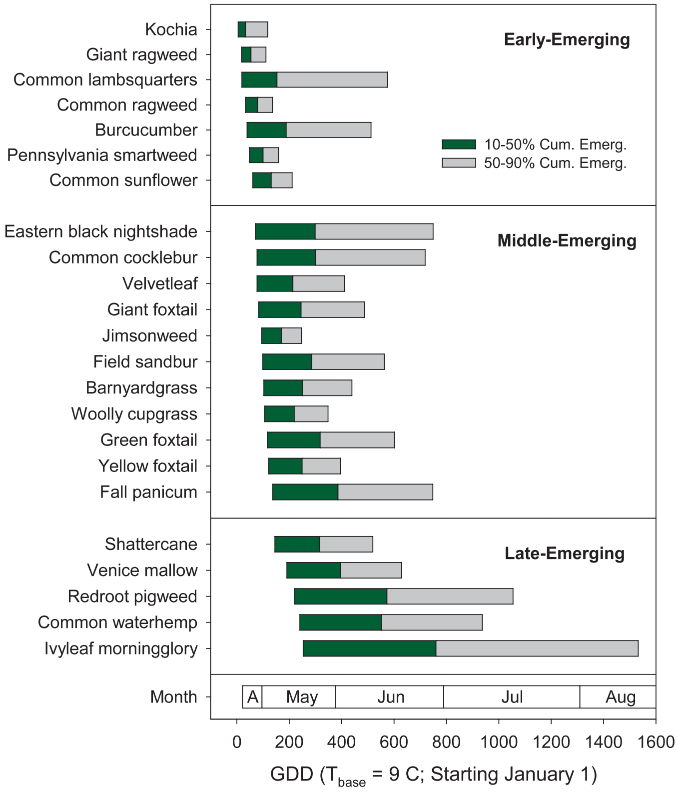

Figure 3. The emergence sequence and duration (10 to 90% cumulative emergence) of 23 summer annual weed species in Iowa according to our "basic models" (base temperature [T_{base}] of 9 C was used across all species). Accumulation of thermal time (growing degree days [GDD]) started on January 1 of each year. Model parameters are shown on Table 5. Monthly accumulated thermal time (GDD) during the study (3-yr average; 1997 to 1999) is added for reference (A = GDD accumulated in April).

for selection of best model in cases of "virtual ties" (when log-likelihood is similar between models), as was observed for 11 species in this study (TT and HTT [ψ_{base} = −1,500 kPa] models with the same T_{base} having the same log-likelihood) (Anderson 2008).

The optimal T_{base} detected for some species in this study differed from T_{base} reported in the literature (Tables 1 and 4). Researchers have used different approaches to obtain appropriate values to develop predictive models for weed emergence and that may lead to contrasting values. Experiments under controlled conditions have been conducted to determine T_{base} (Leon et al. 2004; Masin et al. 2010). Alternatively, T_{base} has been estimated by iterating a set of temperatures until the best statistical fit of a sigmoidal function to the relationship between cumulative emergence and TT is obtained (Izquierdo et al. 2009; Martinson et al. 2007). The information-theoretic model comparison approach (AIC) appeared to be an efficient and statistically appropriate approach to completing the latter assessment (Werle et al. 2014). Moreover, the thresholds detected by this approach in this research are expected to be biologically relevant since they were obtained from an analysis that utilized the progression of cumulative emergence over time under field conditions.

RMSE and ME for the top models in this study ranged from 3.7 to 14.9 and 0.82 to 0.99, respectively. Werle et al. (2014) modeled the emergence pattern of several winter annual weeds and reported RMSE and ME ranging from 13.4 to 23.1 and 0.63 to 0.85, respectively. Roman et al. (2000), validating their predictive model for common lambsquarters emergence, obtained RMSE values ranging from 6.5 to 37.1. Thus, the RMSE and ME values detected in this study indicate good fit of the top models, falling into the range that has been reported in the literature.

Emergence Time and Sequence. Using a constant T_{base} to accumulate heat units (T_{base} = 9 C) across all species enabled us to compare emergence sequence and duration among species under field conditions (Figure 3). A similar approach has been taken elsewhere (Myers et al. 2004; Werle et al. 2014). Even though T_{base} values are known to differ among weed species, this approach allowed us to generate practical results for farmers, crop consultants, and educators. A T_{base} = 9 C was selected to accumulate heat units for our "basic models" because this was the average temperature threshold detected across species in this study (Table 4). Based

Table 5. Weibull function parameters (*lrc* and *pwr*) for the predictive "basic model" using $T_{base} = 9$ C across all species, estimated TT accumulation (GDD) at 10, 50, 90, and from 10 to 90% cumulative emergence, model's goodness of fit (RMSE and ME), and RMSE difference between top and basic model according to Akaike's Information Criterion (ΔRMSE) for each species.[a,b]

Common name	*lrc*	*pwr*	10%	50%	90%	10–90%	RMSE	ME	Δ RMSE
Redroot pigweed	−12.8519	1.9661	220	573	1,054	834	9.47	0.95	1.55
Common waterhemp	−14.6565	2.2635	240	552	937	697	11.68	0.93	1.16
Common ragweed	−9.7789	2.1601	33	79	136	103	9.66	0.89	0.55
Giant ragweed	−6.9708	1.6573	18	54	111	93	10.68	0.79	0.80
Common sunflower	−12.4731	2.4861	61	131	211	150	8.54	0.94	2.45
Common cocklebur	−8.2323	1.3780	77	301	719	642	8.22	0.96	0.01
Common lambsquarters	−4.9031	0.9027	19	153	575	556	11.30	0.87	0.06
Kochia	−3.6356	0.9380	5	33	118	113	7.69	0.82	3.26
Ivyleaf morningglory	−11.7235	1.7119	253	760	1,532	1,279	10.87	0.93	0.72
Burcucumber	−6.6246	1.1953	39	188	512	473	15.25	0.82	0.70
Velvetleaf	−10.2323	1.8395	77	214	410	333	8.69	0.95	0.00
Venice mallow	−15.8153	2.5837	191	395	629	438	9.21	0.95	0.00
Field sandbur	−10.3849	1.7714	99	286	563	464	13.79	0.89	0.80
Barnyardgrass	−12.0571	2.1184	103	250	439	336	7.36	0.96	0.09
Woolly cupgrass	−14.3240	2.5905	106	219	348	242	6.22	0.98	1.01
Fall panicum	−11.1599	1.8125	137	386	748	611	10.09	0.94	2.94
Giant foxtail	−9.9160	1.7364	83	245	488	405	7.65	0.96	0.48
Yellow foxtail	−14.6749	2.5935	121	249	396	275	5.93	0.97	0.61
Green foxtail	−11.1596	1.8738	116	318	602	486	6.33	0.98	0.00
Shattercane	−14.2851	2.4183	145	316	519	374	4.02	0.99	0.28
Pennsylvania smartweed	−12.1498	2.5612	48	100	159	111	9.84	0.91	0.72
Jimsonweed	−16.8142	3.2042	95	170	247	152	8.11	0.95	2.92
Eastern black nightshade	−7.8030	1.3047	71	299	749	678	17.35	0.83	2.50

[a] Abbreviations: T_{base}, base temperature; ψ_{base}, base matric potential; *lrc*, the natural logarithm for the rate of increase; *pwr*, the power to which the explanatory variable (accumulated thermal time) is raised; RMSE, root mean square error; ME, modeling efficiency coefficient; TT, accumulated thermal time; GDD, growing degree days.

[b] RMSE for top model for each species is presented in Table 4.

on the accumulated GDD at the onset of emergence using the "basic models" (10% cumulative emergence), species were classified as early-emerging species (< 70 GDD), middle-emerging species (70 to 140 GDD), and late-emerging species (> 140 GDD). Similar classification has been used by Myers et al. (2004). Moreover, emergence duration was classified as short (< 250 GDD), intermediate (250 to 500 GDD), or extended (> 500 GDD) based on the total accumulated GDD required from 10 to 90% emergence. For reference, according to average estimated soil temperature at 2 cm depth (3-yr average, 1997 to 1999), accumulation of GDD started after March 25, and 70 and 140 GGD were accumulated around April 25 and May 8 at our research site, near Ames.

Early-Emerging Species. Kochia, giant ragweed, common lambsquarters, common ragweed, burcucumber, Pennsylvania smartweed, and common sunflower were the first species to emerge in this study (Table 5; Figure 3). Moreover, giant ragweed, common ragweed, Pennsylvania smartweed, kochia, and common sunflower emerged in a short period; however, burcucumber presented intermediate emergence duration, and for common lambsquarters an extended emergence period was observed.

Middle-Emerging Species. Eastern black nightshade, common cocklebur, velvetleaf, giant foxtail, jimsonweed, field sandbur, barnyardgrass, woolly cupgrass, green foxtail, yellow foxtail, and fall panicum were the next species to emerge (Table 5; Figure 3). Jimsonweed and woolly cupgrass were the only middle-emerging species to emerge in a short period of time. Yellow foxtail, velvetleaf, barnyardgrass, giant foxtail, field sandbur, and green foxtail emerged over an intermediate period. Fall panicum, common cocklebur, and eastern black nightshade emerged over an extended period.

Late-Emerging Species. Shattercane, Venice mallow, redroot pigweed, common waterhemp, and ivyleaf morningglory were the last species to initiate emergence in this study (Table 5; Figure 3). Shattercane and Venice mallow emerged in an intermediate period of time whereas all the other late-emerging species required an extended period to complete emergence.

Myers et al. (2004) found common ragweed and common lambsquarters emerging early in the season in northeastern United States. Velvetleaf, giant foxtail, and yellow foxtail were classified as middle-emerging species, whereas eastern black nightshade was the last species to emerge in their study. Schwinghamer and Van Acker (2008) reported kochia as an early-emerging species in Canada. Stoller and Wax (1973) found giant ragweed and common ragweed emerging during early season, followed by common cocklebur, Pennsylvania smartweed, velvetleaf, and yellow foxtail in Illinois. Ivyleaf morningglory and jimsonweed emerged later in the season in their study. Nussbaum et al. (1985) found kochia emerging early in Texas followed by sunflower, common cocklebur and barnyardgrass, respectively. In Iowa, Hartzler et al. (1999) found common waterhemp emerging later and for an extended period of time when compared to velvetleaf, woolly cupgrass, and giant foxtail. The similarity in our results with those of other published reports of summer annual weed emergence suggests that Figure 3 is a rather robust predictor of the relative time of emergence of these 23 summer annual weeds across much of the U.S. Corn Belt region.

Adaptation of weed emergence pattern in response to intensive management has been reported. Schutte et al. (2012) reported that giant ragweed populations collected in Ohio had an extended biphasic emergence pattern, which differed from the relatively short monophasic emergence pattern observed in this research and by other scientists (Davis et al. 2013; Stoller and Wax 1973). Therefore, it is important to acknowledge that our results should be used as a general guide rather than an absolute predictor of weed emergence timing. Our models have not been independently validated.

Overall, greater seedbank emergence was observed during the first cropping season following burial. However, seeds of many species remained viable in the seedbank and germinated during the subsequent season. Differences in environmental factors across years influenced total seedling emergence. The information-theoretic model comparison approach was a powerful tool for selecting adequate base threshold values and models to predict emergence of different weed species based on observational field studies. It is important to note that the AIC approach allows for selection of the best model within a set of candidate models. Therefore, the inclusion of appropriate models in the pool of candidates prior to model selection is critical. Adding penalty cost to AICc calculation (Equation 3) allowed us to compare TT and HTT when both models behaved similarly. One could argue that when comparing top to basic models (Table 5), the difference in RMSE (ΔRMSE) was very small for some species (i.e., common cocklebur, common lambsquarters, velvetleaf, barnyardgrass). Scientists have used minimization of RMSE as an indicator to estimate ideal threshold values (e.g., T_{base}) for accumulation of heat units in predictive models for weed emergence (Izquierdo et al. 2009). The AIC appeared to be an efficient approach allowing for a more refined search for top models. RMSE was still an adequate goodness-of-fit test, supporting the conclusions obtained when AIC criterion was used for model selection.

Predictive models for 17 out of 23 species had T_{base} ranging from 2 to 15 C, indicating the importance of temperature on summer annual weed seed germination and emergence. Soil moisture was not as critical as expected and including $\psi_{base} = -750$ kPa was only important for four species. This may be due to the fact that precipitation events were common during spring and summer during the study, and soil matric potential rarely dropped below $-1{,}500$ kPa (Figure 1), even during 1997 (driest year in the study; Table 3). Overall, TT was a better descriptor of summer annual weed emergence than HTT. However, different conclusions could have been drawn had this study being conducted in a location where water was a more limiting factor during spring and summer.

Our results may be useful for producers to predict the timing of emergence of multiple weed species. This information can be used to better plan management strategies and identify potential shifts in weed species composition resulting from consistent crop management practices. As an example, early-emerging species, especially those with short emergence duration, can be managed after most seedlings have emerged using burndown herbicides with residual activity or tillage prior to crop sowing. In contrast, middle- and late-emerging species will have to be managed with selective POST herbicides or interrow cultivation after the crop is established. Species with a short emergence period may be controlled with a single management strategy (i.e., POST herbicide application, cultivation), whereas weed species with extended emergence period may require multiple operations. Planting date could also be an important strategy for weed control.

Delayed planting would allow for chemical or mechanical control of early emerging species prior to crop sowing, but can also reduce crop yield potential. In addition, consistent delayed planting of summer annual crops may lead to a shift in species composition to species that emerge later in the season. Early planting would result in earlier canopy closure, resulting in better weed suppression of middle- and late-emerging species by the crop, reducing weed interference. However, consistent early planting of crops may lead to a shift in species composition toward those species that emerge at the same time as the crop. The best management practice used to manage weeds will depend upon the weed species present in the soil seedbank, and diversity of management tactics (e.g., planting dates) will result in fewer shifts in species composition.

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