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Kochia (*Kochia scoparia*) Emergence Profiles and Seed Persistence across the Central Great Plains

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Timing of weed emergence and seed persistence in the soil influence the ability to implement timely and effective control practices. Emergence patterns and seed persistence of kochia populations were monitored in 2010 and 2011 at sites in Kansas, Colorado, Wyoming, Nebraska, and South Dakota. Weekly observations of emergence were initiated in March and continued until no new emergence occurred. Seed was harvested from each site, placed into 100-seed mesh packets, and buried at depths of 0, 2.5, and 10 cm in fall of 2010 and 2011. Packets were exhumed at 6-mo intervals over 2 yr. Viability of exhumed seeds was evaluated. Nonlinear mixed-effects Weibull models were fit to cumulative emergence (%) across growing degree days (GDD) and to viable seed (%) across burial time to describe their fixed and random effects across site-years. Final emergence densities varied among site-years and ranged from as few as 4 to almost 380,000 seedlings m^{-2}. Across 11 site-years in Kansas, cumulative GDD needed for 10% emergence were 168, while across 6 site-years in Wyoming and Nebraska, only 90 GDD were needed; on the calendar, this date shifted from early to late March. The majority (>95%) of kochia seed did not persist for more than 2 yr. Remaining seed viability was generally >80% when seeds were exhumed within 6 mo after burial in March, and declined to <5% by October of the first year after burial. Burial did not appear to increase or decrease seed viability over time but placed seed in a position from which seedling emergence would not be possible. High seedling emergence that occurs very early in the spring emphasizes the need for fall or early spring PRE weed control such as tillage, herbicides, and cover crops, while continued emergence into midsummer emphasizes the need for extended periods of kochia management.

Nomenclature: Kochia, *Kochia scoparia* (L.) Schrad. KCHSC.
Key words: Emergence, seedbank, seed persistence, viability.

Kochia is a major weed in dryland and irrigated crops of the western three-quarters of the United States as well as in pastures, roadsides, and waste areas. Kochia is often observed as the first summer annual weed species to emerge in fields exploiting the limited spring soil moisture in the arid to semi-arid regions of the Great Plains (Friesen et al. 2009). Kochia was introduced from Europe in the mid- to late-1800s. By 1930, it was observed widely across the central United States (Eberlein and Fore 1984). Historically, kochia abundance increased during and following hot, dry years (Blackshaw et al. 2001; Eberlein and Fore 1984; Forcella 1985). Kochia thrives in droughty, nutrient-deficient saline soils where few other plants will grow, allowing it to exploit ecological niches wherever they exist. When kochia invades high-quality agricultural lands, it can grow to 2 m in height, develop a root system to 4 m in depth (Phillips and Launchbaugh 1958), and produce a woody stem more than 2 cm in diameter. Kochia exhibits a tumbling mechanism of seed dispersal whereby the stem dehisces at the base, and the rounded, stiff, mature plants are driven across the landscape by strong winds, dropping seeds as they bounce along at speeds up to 65 km h^{-1} (Baker et al. 2008; Becker 1978; Stallings et al. 1995).

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This very efficient method of seed dispersal provides a rapid means for kochia to spread to new ecological niches, helping generate its reputation as one of the fastest-spreading weeds in the United States and Canada (Blackshaw et al. 2001; Forcella 1985). Kochia seed is known to have very low or no dormancy and thus does not produce a persistent seedbank, unlike many other annual weed species (Schwinghamer and Van Acker 2008; Zorner et al. 1984).

POST weed control had shifted to predominantly nonresidual glyphosate-based programs in several crops and during fallow periods throughout the Great Plains in the mid-2000s, resulting in a dramatic increase in glyphosate-resistant (GR) kochia populations in no-tillage cropping systems (Godar and Stahlman 2015). In Kansas, a GR biotype of kochia was first identified in 2007 with subsequent confirmation of GR biotypes across the Great Plains of the United States and Canada (Godar 2014; Heap 2017; Waite et al. 2013). Additionally, numerous kochia biotypes have developed cross- and multiple resistance to acetolactate synthase, photosystem II, synthetic auxin, and glycine inhibitors that have been traditionally used for weed control in winter wheat and in fallow (Bell et al. 1972; Derksen et al. 2002; Mengistu et al. 2005; Primiani et al. 1990; Thompson et al. 1994; Varanasi et al. 2015; Waite et al. 2013).

The confirmation of GR kochia from geographically distant sites throughout the Great Plains is yet another example of how this ubiquitous dicot weed has successfully used genetic adaptation to thrive and spread. Biological information is needed on the populations found in these areas to aid management of kochia. It is known that kochia emerges very early in the spring and seed persistence in the soil is very short (Schwinghamer and Van Acker 2008; Zorner et al. 1984), but there is no information on geographic influence on emergence patterns, nor is there any evidence that burial depth influences seed viability. Thus, the specific research objectives were to measure and describe the emergence profile of naturally occurring kochia populations to determine how early kochia emergence occurs, the pattern of emergence over time, and the persistence of seed in the soil at field sites across the Great Plains in order to aid producers in managing this weed species.

Materials and Methods

Seedling Emergence Experiment. In February of 2010 and again in 2011, field sites were identified by coauthors across five states—Kansas, Colorado, Wyoming, Nebraska, and South Dakota (Table 1)—where naturally occurring kochia populations were occurring in cropland or non-cropland sites. Crop sites were located within and near the edges of actively cropped fields; non-cropland sites were not being actively cropped (outside field, near buildings), were undisturbed, and had kochia present. Three to eight permanent quadrats were marked at each site in which kochia seedlings were counted and removed as they emerged on a weekly basis. Count data (plants m^{-2}) were converted to cumulative percent emergence and related to cumulative growing degree days (GDD) using a T_{base} air temperature of 0 C for kochia (Schwinghamer and Van Acker 2008). Accumulation of GDD began January 1 in each year using air temperature data from a weather station located near each site.

Seed Burial Experiment. In the fall of 2010 and 2011, seeds were collected from multiple kochia plants located near the emergence quadrats from different emergence cohorts. Up to three emergence cohorts were created by spraying out all emerged kochia and allowing later emerging seedlings to grow and survive until fall. Each cohort was separated in time by 2 wk between spray applications. Bulk seed samples were sent to the Weed Ecology Lab, Department of Agronomy, Manhattan, KS, to be cleaned using sieves and an air-column separator (Seedburo Equipment, 2293 S. Mt. Prospect Road, Des Plaines, IL). Cleaned kochia seeds from each site and cohort were counted using a seed counter (Seedburo 801 Count-A-Pak, Seedburo Equipment, 2293 S. Mt. Prospect Road, Des Plaines, IL) to create 100-seed lot packets. Protective mesh packets each containing 100 kochia seeds were made from 5 by 5 cm squares of 30-mesh wire screen (TWP, 2831 Tenth Street, Berkeley, CA). Packets were sent back to each respective site to be buried. At each site, 15-cm-deep holes were dug in the soil, a wire cage of 6.4-mm mesh (0.25-inch hail screen) was inserted, soil was replaced inside to be able to bury packets at all three different depths within each cage (10 cm, 2.5 cm, and on the surface at 0 cm) or one depth per cage separately (only at Lingle, WY), and a wire cap was placed on top of the cage to keep packets in place and deter rodent predation. Sixteen cages (three burial depths per cage) were established at all sites, except at Lingle, WY, where 48 cages (each burial depth separately) were established in each year. The cages represented four replications with four planned exhumation times for each cohort per site. Seeds collected in fall 2010 were buried by

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Table 1. Mean kochia density and observed range (low and high) for total emergence (plantsm^{-2}) observed across sites and field types identified as cropland or non-cropland in 2010 and 2011.

Year	Site	Field[a]	Total kochia emergence Mean	Low	High
			# m^{-2}		
2010	Lingle, WY	Crop	5,950	341	12,723
	Mitchell, NE	NC	11,074	6,234	15,422
	Scottsbluff, NE	NC	8,480	2,964	12,291
	Stockton, KS	NC	297	91	584
	Hays, KS	Crop	451	159	692
	Hays, KS	NC	331,975	310,500	379,100
	Ness City, KS	NC	387	71	1,227
	Garden City, KS	Crop-NT	10	4	22
2011	Lingle, WY	Crop	2,152	1,369	2,941
	Mitchell, NE	NC	18,218	16,496	19,854
	Scottsbluff, NE	NC	4,780	4,140	6,322
	Stockton, KS	NC	42	29	63
	Manhattan, KS	NC	1,463	414	3,296
	Hays, KS	Crop	21,415	13,390	32,980
	Hays, KS	NC	68,140	61,560	75,930
	Garden City, KS	Crop-NT	58	21	135
	Garden City, KS	Crop-T	86	17	193

[a] Abbreviations: Crop, cropland; NC, non-cropland; NT, no-tillage system; T, tilled system.

December with four exhumations planned for March and October of 2011 and 2012. Another set of packets was buried with seeds collected in fall 2011 and exhumations in March and October of 2012 and 2013.

After packets were exhumed, they were sent to the Weed Ecology Lab, Department of Agronomy, Manhattan, KS, where seeds were removed from each packet and placed in individual petri dishes with filter paper and tap water in a growth chamber set at 20/10 C day/night temperatures and a 12-h photoperiod. Germination counts were taken every 3 to 4 d for a total of 21 d; a seed was considered germinated when its radicle was greater than 2 mm in length. Petri dishes were allowed to dry for 30 d and then rewetted; subsequently germinating seeds were counted or remaining seeds were tested with a “crush” test to identify hard, viable seed (Borza et al. 2007; Sawma and Mohler 2002). The percentage of viable seed from each exhumation was determined based on $n = 100$ total seed packet^{-1} for each burial year, site, cohort, and depth of burial (Ullrich et al. 2011).

Statistical Modeling Approach. A nonlinear mixed-effects modeling (NLME) method was used to analyze both the seedling emergence data and seed persistence data. To be specific, for the seedling emergence data, it was the relationship between cumulative percent kochia emergence and cumulative GDD, while for the seed burial data it was the relationship between percent viable seed and length of seed burial, based on the following flexible mixed-effects Weibull model (Clay et al. 2014; Davis et al. 2013; Ratkowski 1983):

$$y_{ij} = \varnothing_{1i} - \varnothing_{2i}\exp\left[-\exp(\varnothing_{3i})x_{ij}^{\varnothing_{4i}}\right] + \in_{ij} \qquad [1a]$$

where y_{ij} is the jth response (either cumulative percent emergence or percent viable seed) at ith site-year, x_{ij} is the jth value of the cumulative GDD for seedling emergence data or the length of seed burial (fraction of year) for the viable seed data at ith site-year; $\varnothing_{1i}$ (*Asym*) represents the asymptote as $x \to \infty$ and $\varnothing_{2i}$ (*Drop*) represents the difference between asymptote $\varnothing_{1i}$ and asymptote as $x \to 0$; the logarithm of the rate constant (*lrc*) is $\varnothing_{3i}$; and the shape parameter (*pwr*) is $\varnothing_{4i}$.

$$\varnothing_i = \begin{bmatrix} \varnothing_{1i} \\ \varnothing_{2i} \\ \varnothing_{3i} \\ \varnothing_{4i} \end{bmatrix} = \begin{bmatrix} \beta_1 \\ \beta_2 \\ \beta_3 \\ \beta_4 \end{bmatrix} + \begin{bmatrix} b_{1i} \\ b_{2i} \\ b_{3i} \\ b_{4i} \end{bmatrix} = \beta + \boldsymbol{b}_i$$

$$\mathbf{b_i} \sim N(0, \Psi), \in_{ij} \sim N\left(0, \sigma^2\right) \qquad [1b]$$

where the site-year-specific parameter vector, $\varnothing_i$, consists of a vector of fixed effects (β) and a vector of random effects ($\boldsymbol{b}_i$) associated with the ith group,

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with a variance–covariance matrix (ψ) that is assumed to be a diagonal matrix. The random errors (ϵ_{ij}) are assumed to be independent and identically normally distributed. Note that when *Drop* ($\varnothing_{2i}$) is positive, then the expected regression function has an increasing trend and it is used to model the cumulative percent emergence, and when *Drop* ($\varnothing_{2i}$) is negative, then the expected regression function has a decreasing relationship and it is used to model percent viable seed data over time.

The model fit was based on maximum likelihood estimation method using the library 'nlme' of R v. 3.3.1 (R Core Team 2016). To determine whether a reduced model with fewer parameters should be used, or which random effects should be eliminated, or how useful some of the covariates were to explain between-group variability, we used common statistical model selection criteria such as the Akaike information criterion (AIC), Bayesian information criterion (BIC), or likelihood ratio test.

Seedling emergence data were modeled separately by two groups: 11 site-years for Kansas and 6 site-years for Wyoming and Nebraska. Seedbank persistence data were modeled separately by two groups: 10 site-years that had multiple-cohort data and 6 site-years that had single-cohort data. For single-cohort data, significant covariates were identified that included site, field type (cropland or non-cropland), and year of seed burial and used Equation 2:

$$\varnothing_{3i} = \beta_3 + \gamma_1 site_{1i} + \gamma_2 site_{2i} + \gamma_3 field_{3i} + \gamma_4 year_i + b_{3i} \qquad [2]$$

Cumulative GDD and calendar date for the start (10% emergence) and GDD for the midpoint (50%) and end (90%) of kochia emergence were calculated based on best NLME model fit for each site-year.

Results and Discussion

Over the course of the study, observations of kochia seedling emergence and seedbank persistence were made at sites ranging from Garden City, KS, in the south to Brookings, SD, in the north, and from Fort Collins, CO, in the west to Manhattan, KS, in the east. A total of 17 site-years had useful observations for seedling emergence (Table 1), and 16 site-years had useful observations for seedbank persistence.

Seedling Emergence. The maximum number of kochia that emerged varied widely across the sites and field types in 2010 and 2011 but are not atypical of kochia densities (Table 1). For example, lowest observed density was 4 plants m^{-2} in one plot in 2010 at Garden City, KS, in a no-tillage cropland environment with several years of aggressive herbicide management (RS Currie, personal observation), and up to 379,100 seedlings m^{-2} in a plot in a non-cropland environment in 2010 at Hays, KS (Table 1). Average kochia densities in cropland environments were 2,137 and 4,755 seedlings m^{-2} in 2010 and 2011, respectively, while in non-cropland environments, populations were 70,440 and 18,530 seedlings m^{-2} in 2010 and 2011, respectively. The increased number of seedlings in non-cropland environments was likely due to high plant density and seed rain from the previous year when no active weed control was applied in those environments. Average kochia density observed in

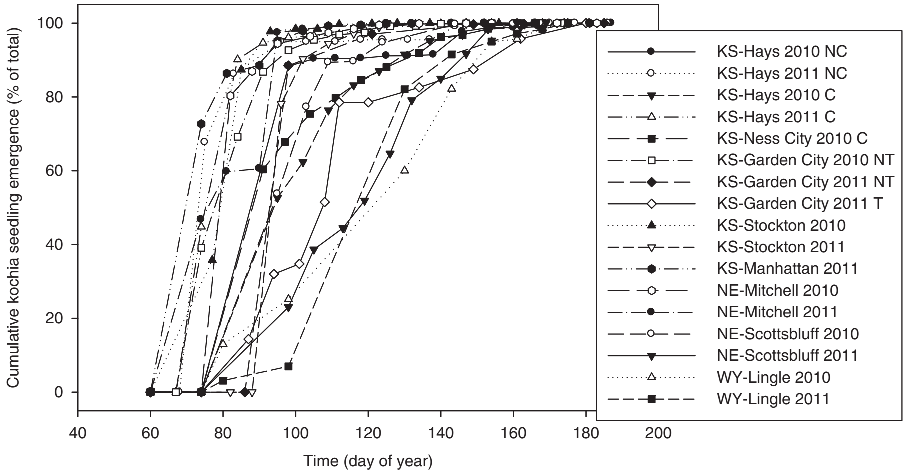

Figure 1. Cumulative kochia seedling emergence, by day of year, for 17 site-years across the Great High Plains region of the United States. NC, non-cropland; C, cropland; NT, no-tillage system; T, tilled system

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Table 2. Summary of fixed and random effects for the most parsimonious nonlinear mixed-effects model of kochia cumulative seedling emergence following a Weibull response function to cumulative GDD across 11 site-years in Kansas.

Fixed effects	Coefficient	SD	df	*t*-value	P-value	Random effects	SE
Asym	99.98	3.03	611	33.01	<0.0001	*Asym*	9.39
Drop	182.57	16.38	611	11.15	<0.0001	*Drop*	48.61
lrc	−5.47	0.05	611	− 133.64	<0.0001	Residual	15.21

fields in Manitoba was 2,292 seedlings m^{-2} and was characterized as a much greater density level than typically observed in cultivated fields in Manitoba (Schwinghamer and Van Acker 2008). Typical end-of-season populations observed in western Nebraska in untreated check plots were 16 to 24 kochia plants m^{-2} at soybean harvest, but in the following winter wheat crop, kochia densities ranged from 39 to 1,950 plants m^{-2} depending on year (Wicks et al. 1997). Kochia population size can increase quickly if left uncontrolled from one year to the next.

Kochia seedlings were initially observed in 2010 by the middle of March (day of year [DOY] 70), and in 2011 by the end of February (DOY 60) and early March depending on the site (Figure 1). Across most site-years, seedling emergence quickly achieved 100% cumulative emergence, often within 2 to 3 wk after initial observations. However, the rate of seedling emergence varied widely among site-years when described using DOY (Figure 1). This is not unusual when examining emergence timing across a wide geography, as similar observations were seen with giant ragweed (*Ambrosia trifida* L.) (Davis et al. 2013) or common sunflower (*Helianthus annuus* L.) (Clay et al. 2014) across the midwestern United States. Kochia seedlings are known to be the first summer annuals to emerge (Werle et al. 2014), but DOY will vary across the Great Plains region.

Seedling emergence patterns for kochia populations across 11 site-years in Kansas were analyzed separately from the 6 site-years in Nebraska and Wyoming, using NLME. After comparison among a pool of candidate models, the most parsimonious NLME Weibull model for seedling emergence in Kansas had a fixed shape parameter value for $\O_{4i}$ (*pwr*) = 1, and only $\O_{1i}$ (*Asym*) and $\O_{2i}$ (*Drop*) had random effects using Equation 1 (Table 2). The type of field (cropland or non-cropland) was not significant in explaining the variation in seedling emergence patterns, thus this model predicted kochia seedling emergence among the 11 site-years across Kansas (Tables 2 and 3). The quality of the fitted NLME model can be visualized in Figure 2. The solid line gives the population average (fixed) predicted cumulative percent seedling emergence for the 11 site-years in Kansas, while the dashed line shows the specific prediction for each site-year, which is in good agreement with the observed values and site-year-specific parameter estimates shown in Table 3. In general, seedling emergence at Hays (4 site-years) was more rapid (dashed line to the left of fixed line) than that observed in Garden City

Table 3. Weibull model parameters (*Asym* and *Drop*) for the predictive seedling emergence model, calendar date for 10% emergence, and estimated GDD for 10%, 50%, and 90% cumulative seedling emergence for each of 11 site-years across field types in Kansas.

Site	Year	Field[a]	*Asym*	*Drop*	Calendar date for 10%	10%	50%	90%
							GDD	
Garden City	2010	Crop-NT	−14.66	28.35	March 30, 2010	245	425	2,369
Garden City	2011	Crop-NT	−11.55	57.05	March 21, 2011	266	436	2,400
Garden city	2011	Crop-T	−9.45	77.71	March 21, 2011	279	443	1,473
Ness City	2010	NC	3.63	−26.09	March 13, 2010	122	255	581
Hays	2010	Crop	6.83	17.95	March 10, 2010	173	300	590
Hays	2010	NC	7.65	−75.14	March 24, 2010	23	148	430
Hays	2011	Crop	8.28	−64.78	January 28, 2011	43	168	444
Hays	2011	NC	7.05	−37.05	February 6, 2011	96	223	511
Stockton	2010	NC	3.53	−2.41	March 23, 2010	156	289	616
Stockton	2011	NC	−11.21	44.71	March 21, 2011	252	421	2,387
Manhattan	2011	NC	9.91	−20.29	March 3, 2011	115	237	500

[a] Abbreviations: Crop, cropland; NC, non-cropland; NT, no-tillage system; T, tilled system.

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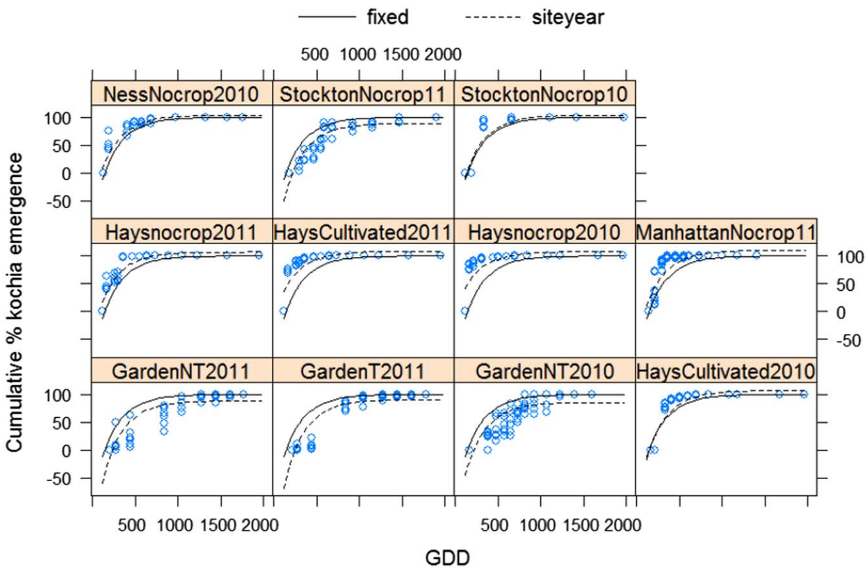

Figure 2. The site-year-specific predicted cumulative percent of emergence (dashed line) and fixed population predictions (solid line) by fitting nonlinear mixed-effects Weibull model of Kochia seedling emergence for 11 site-years in Kansas. GDD, growing degree days.

(3 site-years), which was slower (dashed line to the right of fixed line).

Seedling emergence patterns for kochia populations observed in Wyoming and Nebraska (6 site-years) were also modeled using NLME, and based on comparison among a pool of candidate models using AIC, the most parsimonious NLME Weibull model was constrained by equality of *Asym* and *Drop* parameters, i.e., $\varnothing_{1i} = \varnothing_{2i}$ and only $\varnothing_{1i}$ (*Asym*) and $\varnothing_{4i}$ (*pwr*) had random effects in Equation 1 (Table 4). The quality of the fitted NLME model for 6 site-years across Wyoming and Nebraska can be visualized in Figure 3. The solid line gives the population average (fixed) predicted percent cumulative seedling emergence, while the dashed line shows the site-year specific prediction, which is in good agreement with the observed values. In general, seedling emergence across Wyoming and Nebraska in 2010 was slower and variable as compared with 2011 (Table 5; Figure 3).

The predicted cumulative GDD needed for 10%, 50%, and 90% cumulative kochia emergence in Kansas, based on the average (fixed) model, were 168, 308, and 692 GDD, respectively, while for the Nebraska and Wyoming populations, the GDD needed were 90, 156, and 230 GDD. Moving north, fewer GDD were required for kochia seedling emergence. This may indicate a lower critical temperature for kochia in more northern latitudes and would need to determined. In its more northerly range in Manitoba, field emergence of kochia was observed to begin at 50 cumulative GDD (T_{base} 0 C, soil temperature at 2.5-cm depth); this was typically accumulated by April 17, and kochia emergence continued throughout the growing season, although in small numbers after the initial flush (Schwinghamer and Van Acker 2008). Werle et al. (2014) found that kochia was the first summer annual that emerged in their study in Iowa conditions, with a short rapid window of emergence beginning in early April through mid-May. Anderson and Nielsen (1996) observed kochia beginning to emerge in the field at Akron, CO, in early April, with 80% of the seedlings emerging between April 11 and June 20 from 1987 to 1990.

Although kochia is a C_4 plant that thrives under hot temperatures, its seed readily germinates very early in the spring when snow is still on the ground, and kochia plants in the early seedling stage are very cold tolerant, usually surviving spring freezing nighttime temperatures (Chepil 1946; Dyer et al. 1993). As soon

Table 4. Summary of fixed and random effects for the most parsimonious nonlinear mixed-effects model of kochia cumulative seedling emergence following a Weibull response function to cumulative GDD across 6 site-years in Wyoming and Nebraska.

Fixed effects	Coefficient	SD	df	*t*-value	P-value	Random effects	SE
Asym	95.72	1.09	397	87.47	<0.0001	*Asym*	2.46
lrc	– 17.73	0.89	397	– 19.82	<0.0001	*pwr*	0.11
pwr	3.45	0.18	397	19.20	<0.0001	residual	7.20

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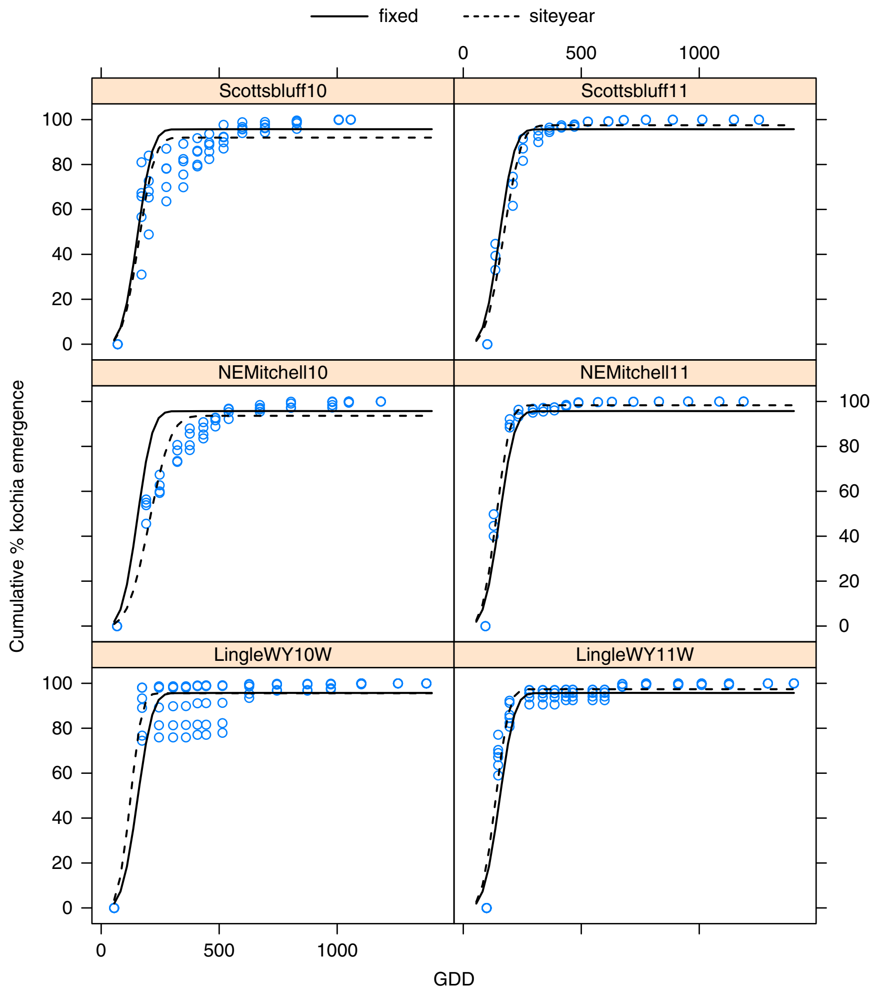

Figure 3. The site-year-specific predicted cumulative percent of emergence (dashed line) and fixed population predictions (solid line) by fitting nonlinear mixed-effects Weibull model of Kochia seedling emergence for 6 site-years in NE and WY. GDD, growing degree days.

as there is sufficient moisture in the early spring, kochia will initiate germination and emergence (Werle et al. 2014). Often, this is less moisture than required for soil-applied herbicides to be effective for kochia control (Sebastian et al. 2017).

Cropland sites had an emergence pattern that was later and more prolonged compared with non-cropland sites, in general. For example, when comparing the two sites in Hays, KS, kochia emergence was 2 wk later in the cropland site compared with the non-cropland site in 2010 (Table 3). Kochia is capable of adapting to chosen weed control practice, as was demonstrated in western Nebraska, where kochia biotypes were selected for delayed emergence until after the soil-applied herbicide isoxaflutole had dissipated compared with plots without a residual herbicide (Sbatella and Wilson 2010). In cropland environments with

Table 5. Weibull function parameters (*Asym* and *pwr*) for the predictive seedling emergence model, calendar date for 10% emergence, and estimated GDD for 10%, 50%, and 90% cumulative seedling emergence for each of the 6 site-years in Wyoming and Nebraska.

Site	Year	Field[a]	*Asym*	*pwr*	Calendar date for 10% emergence	10%	50%	90%
Lingle, WY	2010	Crop	−1.07	0.16	March 23, 2010	86	149	220
Lingle, WY	2011	Crop	−0.50	0.07	March 2, 2011	88	152	219
Mitchell, NE	2010	NC	1.23	−0.18	March 22, 2010	96	166	253
Mitchell, NE	2011	NC	−0.39	0.06	March 5, 2011	88	152	218
Scottsbluff, NE	2010	NC	0.17	−0.03	March 21, 2010	92	160	254
Scottsbluff, NE	2011	NC	0.57	−0.08	March 1, 2011	91	158	229

[a] Abbreviations: Crop, cropland; NC, non-cropland.

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Table 6. Summary of fixed and random effects for the most parsimonious nonlinear mixed-effects model of kochia seedbank persistence following a Weibull response function to length of seed burial across 10 site-years and multiple cohorts of kochia seed in Wyoming, Nebraska, Colorado, and Kansas.

Fixed effects	Coefficient	SD	df	*t*-value	P-value	Random effects	SE
Asym	−9.72	1.01	1702	−9.63	<0.0001	*Asym*	2.55
Drop	−114.16	1.10	1702	−104.19	<0.0001	*lrc*	0.37
lrc	0.45	0.07	1702	6.33	<0.0001	Residual	14.44

previous aggressive weed management, such as both years at Garden City, the overall emergence was low, with maximum of 22 to 193 seedlings m^{-2}, but required more than 1,450 GDD in a tilled environment and more than 2,350 GDD in no-tillage cropland sites to reach 90% cumulative emergence (Table 3), demonstrating a very prolonged emergence pattern and opportunity for selection of later-emerging individuals.

Seed Burial. In this study, multiple cohorts of kochia plants whose seed were harvested, buried, and exhumed as separate cohorts were evaluated for 10 site-years. These included two from Colorado (dryland and irrigated sites with seed buried in 2010), four from Nebraska (Mitchell and Scottsbluff with seed buried in 2010 and 2011), three from Kansas (Garden City no-tillage 2010, and Stockton 2010 and 2011), and one from Wyoming (2010). For these data, after comparison among a pool of candidate models based on AIC and BIC, the most parsimonious NLME Weibull model for percent viable seed as function of length of seed burial had a fixed shape parameter value, $\emptyset_{4i}$ (*pwr*) = 1, and only $\emptyset_{1i}$ (*Asym*) and $\emptyset_{3i}$ (*lrc*) had random effects in Equation 1. Parameter estimates for this best model are given in Tables 6 and 7. The depth of burial (0, 2.5, or 10 cm) had no effect on seedbank persistence, and type of field with respect to cropland or non-cropland did not contribute enough information to be included in the model. The quality of the fitted NLME model can be visualized in Figure 4. The solid line gives the population average (fixed) predicted percent viable seed for the 10 site-years and at each burial depth with multiple cohorts, while the dashed line shows the specific prediction for each site-year and burial depth, which is in good agreement with the observed values. By the first exhumation at 0.5 yr, there was variability in percent viable seed, but by the fourth exhumation at 2.0 yr, percent of viable seeds from all site-years and burial depths was very low (<2%) (Figure 4).

A total of 6 site-years had single cohorts of kochia seed buried, including four in Kansas (Hays crop and non-cropland in 2010 and Garden City tilled and no-tillage environments in 2011) and two in South Dakota (Brookings, 2010 and 2011). For these data, the most parsimonious NLME Weibull model for percent viable seed as function of length of seed burial had a fixed shape parameter value, $\emptyset_{4i}$ (*pwr*) = 1, and $\emptyset_{3i}$ (*lrc*) had random effects in Equation 1 (Table 8) as well as significant covariates for site, field type, and year of burial as described by Equation 2. The quality of the fitted NLME model can be visualized in Figure 5 (Table 9).

Seeds buried in the fall and exhumed in March (0.5 yr, within 6 mo) were viable, intact, and had high germination capacity, but there was some variation

Table 7. Weibull function parameters (*Asym* and *lrc*) for the predictive percent viable seed for each seed burial depth across 10 site-years and multiple cohorts in Wyoming, Nebraska, Colorado, and Kansas.

		0 cm		2.5 cm		10 cm	
Site	Year	*Asym*	*lrc*	*Asym*	*lrc*	*Asym*	*lrc*
Lingle, WY	2010	−2.33	−0.33	0.84	0.12	0.70	0.10
Mitchell, NE	2010	−2.36	−0.34	−2.12	−0.30	−2.14	−0.31
Mitchell, NE	2011	−2.15	−0.31	−0.33	−0.05	−0.63	−0.09
Scottsbluff, NE	2010	−2.07	−0.30	−2.10	−0.30	−2.45	−0.35
Scottsbluff, NE	2011	−2.46	−0.35	−1.84	−0.26	−1.86	−0.27
Colorado – dryland	2010	3.54	0.51	3.94	0.56	3.06	0.44
Colorado – irrigated	2010	−1.22	−0.17	−1.13	−0.16	−1.01	−0.14
Stockton, KS	2010	3.13	0.45	5.46	0.78	5.01	0.72
Stockton, KS	2011	−0.07	−0.01	0.06	0.01	−1.86	−0.27
Garden City, KS	2010	−1.54	−0.22	2.24	0.32	3.68	0.53

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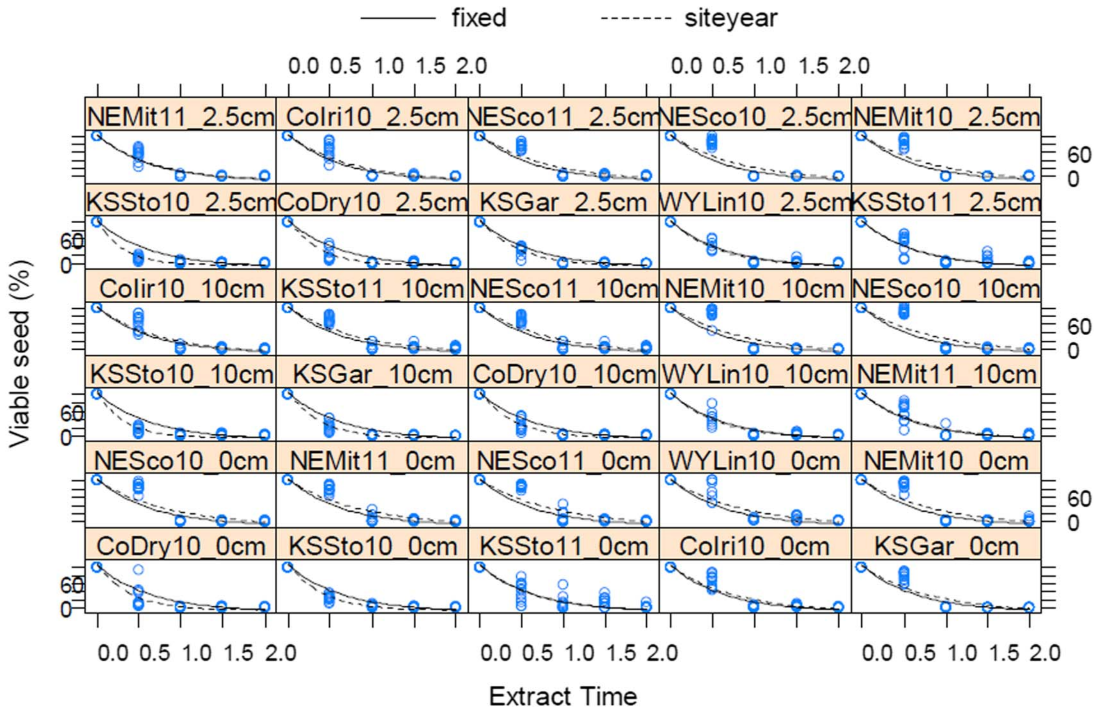

Figure 4. The predicted percent viable seed (dashed line) and fixed population predictions (solid line) for the nonlinear mixed-effects Weibull model of kochia populations across site-years and burial depths with multiple cohorts. Site and year abbreviations: NEMit, Mitchell, NE; NESco, Scottsbluff, NE; CoIri, Colorado-irrigated; KSSto, Stockton, KS; CoDry, Colorado-dryland; KSGar, Garden City, KS; WYLin, Lingle, WY; 10, buried seed in 2010; 11, buried seed in 2011.

among sites-years and burial depths (Figures 4 and 5). This first exhumation period corresponds to the time when kochia typically emerges in the Great Plains and highlights why such large populations can be observed each year in the early spring.

The majority (>95%) of seed buried in these experiments did not persist for 2 yr (Figures 4 and 5). By the second exhumation period in October (nearly 1 yr after burial), remaining seeds were significantly less viable. There was much seed mortality over the first summer, as demonstrated by these low levels of viable seed. The share of remaining viable seed decreased through the last two exhumation dates (to 2 yr after burial), with <2% of seed remaining viable. Some site-years had no viable seed remaining in any of the burial packets, as at Garden City, KS, in 2010, or in six of nine cohort-by-burial depth packets in the irrigated environment at Fort Collins, CO, in 2010 (unpublished data). The range in percent viable seed also decreased with time.

The lack of a seed burial effect on kochia seedbank persistence in this study is not typical for most annual weed species. Burial of seed is often considered a mechanism for seeds to maintain viability and persist until returned to the soil surface for germination and emergence. These results did not show that burial depth increased or decreased seed persistence. Zorner et al. (1984) observed that initially nondormant

Table 8. Summary of fixed and random effects for the most parsimonious nonlinear mixed-effects model of kochia seedbank persistence (percent viable seed) following a Weibull response function in response to length of seed burial across a single cohort of kochia seed using Equations 1 and 3.

Fixed effects	Coefficient	SE	df	*t*-value	P-value	Random effects	SE
lrc.(intercept)	−1,490	286	334	−5.20	0	*lrc*	0.13
lrc.site (Hays, KS)	0.31	0.21	334	1.51	0.13	Residual	10.08
lrc.site (Brookings, SD)	−0.48	0.15	334	−3.21	0		
lrc.field	−0.54	0.15	334	−3.71	0		
lrc.year	0.74	0.14	334	5.21	0		
Asym	−1.72	0.93	334	−1.84	0.07		
Drop	−103.8	1.48	334	−70.29	0		

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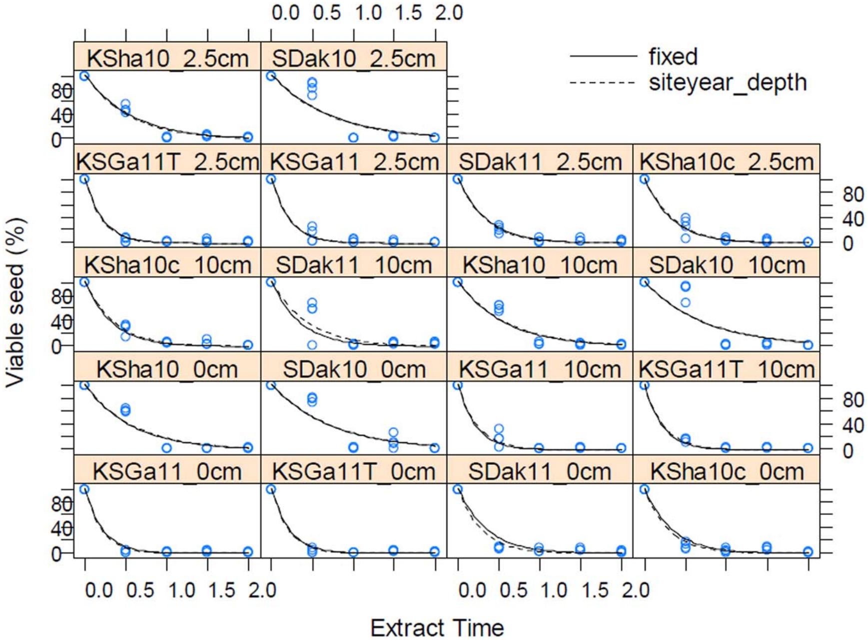

Figure 5. The predicted percent viable seed (dashed line) and fixed population predictions (solid line) for the NLME Weibull model of kochia populations across site-years and burial depths with a single cohort. Site-year abbreviations: KSha10, Hays, KS, 2010, noncropland; KSha10c, Hays, KS, 2010, cropland; SDak10, Brookings, SD, 2010; SDak11, Brookings, SD, 2011; KSGa11T, Garden City, KS, 2011, tilled system; KSGa11, Garden City, KS 2011, no-tillage system.

kochia seed had slightly longer persistence when buried at 10, 15, or 30 cm, but after 1.5 to 2 yr of burial, 3% or less seed was still viable across all depths. Other studies have shown that even if kochia seed germinated at these depths, seedlings cannot emerge from greater than 5 cm in the soil (Schwinghamer and Van Acker 2008; Zorner et al. 1984).

Weed Management Recommendations Based on Germination Ecology of Kochia. An integrated kochia management approach is needed. Predictions of kochia emergence based on GDD as presented here could be used in determining timing of control practices as well as crop planting dates. Early and rapid kochia emergence may make this weed susceptible to a stale seedbed approach, where weeds are controlled prior to crop planting and emergence. For soil-applied herbicides to be effective, fall or very early spring pre-planting applications are required. Kochia can germinate and emerge under very low temperature and low-moisture requirements and, therefore, identifying herbicides that can be activated and effective with low-moisture conditions are critical (Sebastian et al. 2017).

Table 9. Weibull function parameters for *lrc* [ln(rate constant)] for each of the seed burial depths across 6 site-years for kochia populations with a single cohort.

Site	Year	Field[a]	0 cm	2.5 cm	10 cm
Hays, KS	2010	Crop	0.13	−0.06	−0.08
Hays, KS	2010	NC	−0.02	0.06	−0.04
Garden City, KS	2011	Crop-T	0.08	0.06	−0.07
Garden City, KS	2011	Crop-NT	0.07	−0.03	−0.10
Brookings, SD	2010	Crop	−0.01	0.02	−0.01
Brookings, SD	2011	Crop	0.20	0.04	−0.24

[a] Abbreviations: Crop, cropland; NC, non-cropland; NT, no-tillage system; T, tilled system.

The first flush of kochia is usually very dense and can appear rapidly in late February and very early March in the central Great Plains. Soil- and foliar-active herbicides applied prior to crop planting and emergence may control a majority of the kochia seedlings, resulting in a much lower-density kochia population that would need to be controlled with subsequent soil-residual herbicides or selective herbicide applications after crop emergence. In many cases, more diverse herbicide options may be available for controlling weeds prior to crop emergence as compared with after crop emergence for crops such as corn (*Zea mays* L.), grain sorghum [*Sorghum bicolor* (L.) Moench], or soybean [*Glycine max* (L.) Merr.]. Few options are available for sugar beet (*Beta vulgaris* L.) production systems. Unfortunately, single and multiple herbicide–resistant kochia biotypes are already present across the Great Plains (Thompson et al. 1994; Varanasi et al. 2015; Waite et al. 2013).

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Consequently, there is a limited opportunity to diversify herbicide modes of action to minimize further selection for herbicide resistance or to control kochia biotypes already resistant or tolerant to herbicides that are available for a crop after it emerges.

The rapid emergence patterns may be exploited to develop effective cultural and mechanical management strategies. Early tillage may be effective, particularly given the results from this research indicating that kochia seed deeper in the soil that may be exhumed by tillage may have a very low percent viability. Tillage options, however, may be limited in many areas where kochia is common because of no-tillage cropping systems being used to conserve soil moisture in the Great Plains.

The very low dormancy and short persistence of kochia seed as demonstrated in this research suggests that it may be possible to quickly deplete seedbanks if kochia is aggressively managed using cultural and mechanical practices. Including rotational crops that are highly competitive with kochia may effectively reduce seedling survival and fecundity and thus help to reduce new additions to the seedbank (Esser 2014) and permit crops with limited kochia control options to be added back into the rotation sequence. For example, monocot crops such as wheat (*Triticum aestivum* L.) and corn enable the use of some highly effective herbicide options, whereas dicot crops such as sunflowers, soybeans, sugar beet, and pulse crops. have fewer effective herbicide options, particularly after crop emergence. Including cover crops in the rotation sequence can sometimes be an effective component of an integrated weed management program. Spring-sown cover crops would be at a competitive disadvantage, since the crop and kochia are likely to emerge together (Petrosino et al. 2015). In the Great Plains, fall-established cover crop systems were shown to effectively suppress kochia density and reduce biomass, as the winter annual cover crops were able to develop an aggressive canopy earlier in the spring before kochia emerged (Petrosino et al. 2015).

Kochia has become a significant weed problem across the Great Plains because it has developed herbicide-resistant biotypes, emerges very early in the spring before other summer annual weed species, and disperses seed by tumbling across the landscape. PRE weed control, including tillage, herbicides, or cover crops, needs to be initiated in the fall or very early spring (February) to reduce or eliminate seedling emergence and thus reduce seed production. Short persistence of seed in the soil would assist in depleting seedbanks, and a community-wide effort to minimize kochia plant and seed movement would reduce the impact this weed species has in the Great Plains region.

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